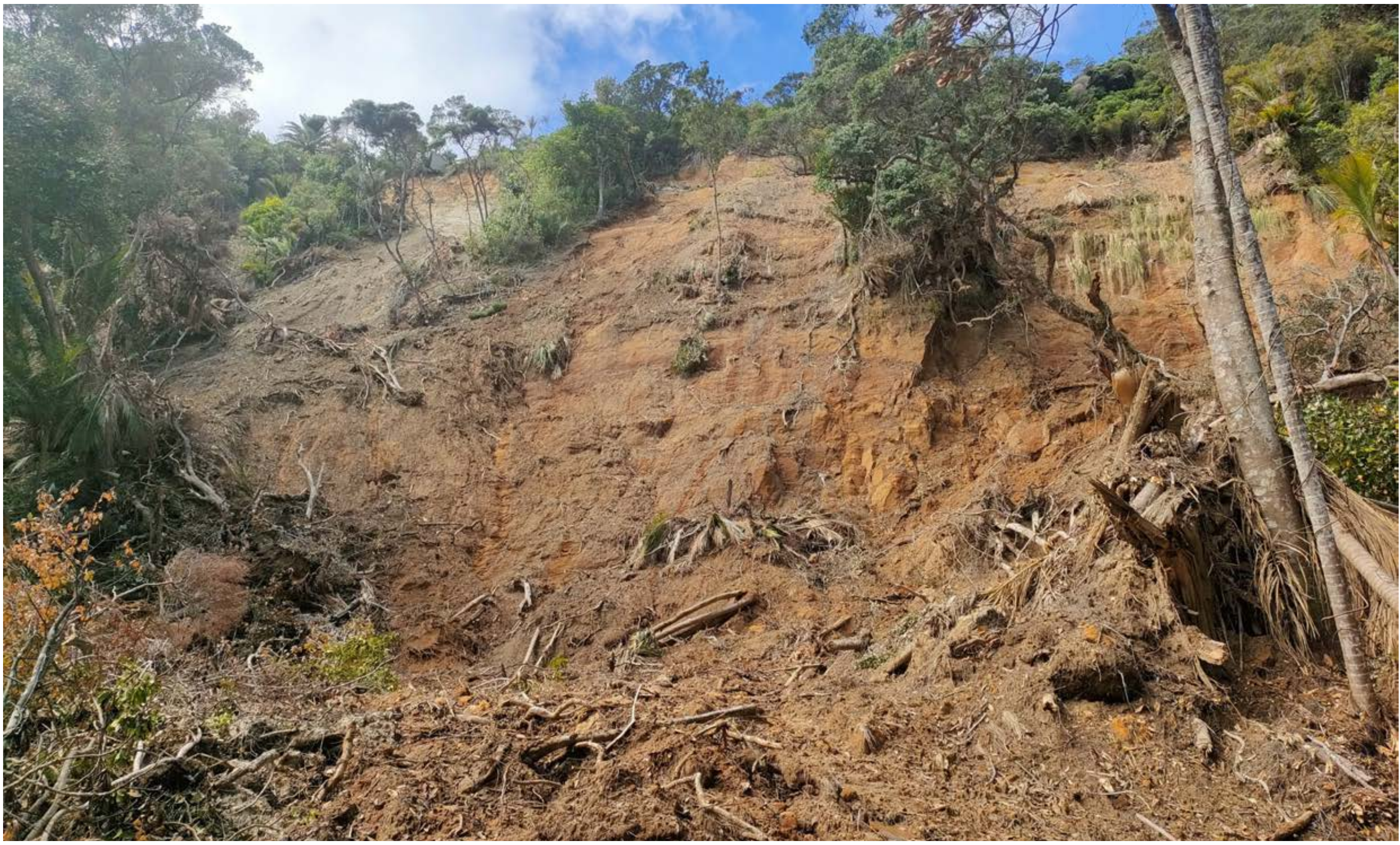
Waitakere Coastal Communities Landslide Risk Assessment

Overall Report - Muriwai

Auckland Council

15 May 2024

→ **The Power of Commitment**



Project name	Waitakere Coastal Communities Landslide Risk Assessment
Document title	Waitakere Coastal Communities Landslide Risk Assessment | Overall Report - Muriwai
Project number	12612462
File name	12612462_Overall Report_FINALRev2.docx

Status Code	**Revision**	**Author**	**Reviewer**		**Approved for issue**		
			Name	**Signature**	**Name**	**Signature**	**Date**
S4	0	Matt Howard	Don Macfarlane	D Macfarlane	Matt Howard	MHoward	03/11/2023
S4	1	Matt Howard	Don Macfarlane	D Macfarlane	Matt Howard	MHoward	30/04/2024
S4	2	Matt Howard	Don Macfarlane	D Macfarlane	Matt Howard	Roy Pearson	15/05/2024
[Status code]							
[Status code]							

GHD Limited
Contact: Matt Howard, Technical Director - Engineering Geologist | GHD
27 Napier Street, GHD Centre Level 3
Freemans Bay, Auckland 1010, New Zealand
T +64 9 370 8000 | **F** +64 9 370 8001 | **E** aklmail@ghd.com | **ghd.com**

→ The Power of Commitment

Contents

Table index

Appendices

1. Introduction

1.1 Purpose of this report

GHD has been engaged by Auckland Council (AC)[1] to carry out Quantitative Landslide Risk Assessments (QRA) as well as to provide associated landslide risk management advice and geotechnical investigations in the Muriwai area (‘the study area’). The purpose of this assessment is to carry out a Quantitative Landslide Risk Assessment (QRA) for the Muriwai area (‘the study area’). The QRA is to estimate the risk of Loss of Life to individuals at these properties. The outcome of the QRA will be used to inform subsequent property risk categorisation and building placard designation review by AC. This report version is the final issue. It has taken into account any information provided by the landowner either through the Auckland Council feedback portal or through Auckland Council Recovery Office communication channels.

The purpose of this ‘overall report’ is to combine and summarise the various GHD geotechnical assessments for Muriwai in a single document. The focus of the report is on the large-scale hazard from the 80 m-high escarpment to the east of Muriwai township that experienced damaging landslides from the escarpment in February 2023 (see Figure 1). Our study includes elements that support a risk assessment that provides a quantified loss-of-life risk from landslides to occupants of dwellings.

This report contains appended reports, which should be read in conjunction with it.

1.2 Background

Two significant rainfall events affected the Waitakere area in late January and early February 2023, resulting from the impacts of ex-tropical cyclones Hale and Gabrielle, respectively.

The Cyclone Gabrielle weather event of 14 February 2023 resulted in widespread catastrophic flooding and slope instability in the settlement of Muriwai where several debris avalanches (which included rocks and trees) occurred, some of which turned into saturated debris flows as they travelled downslope. These flows resulted in damage to buildings and infrastructure. Two fatalities occurred due to impact of landslides on private dwellings. This tragic event was similar to a 1965 storm event that also claimed two lives.

Following the recent event, rapid building assessment of residential properties was undertaken in Muriwai, with some houses having access by owners restricted (a yellow placard – e.g. access in daylight hours only) and some for which no access was permitted (a red placard). Dwellings that retained unrestricted access were white placarded.

---

[1] As part of contract CW198379, Master Services Agreement CCCS: CW74240 dated 7/09/2019, subsequent work item ‘Waitakere Coastal Communities Landslide Risk Assessment’, dated 26/04/2023

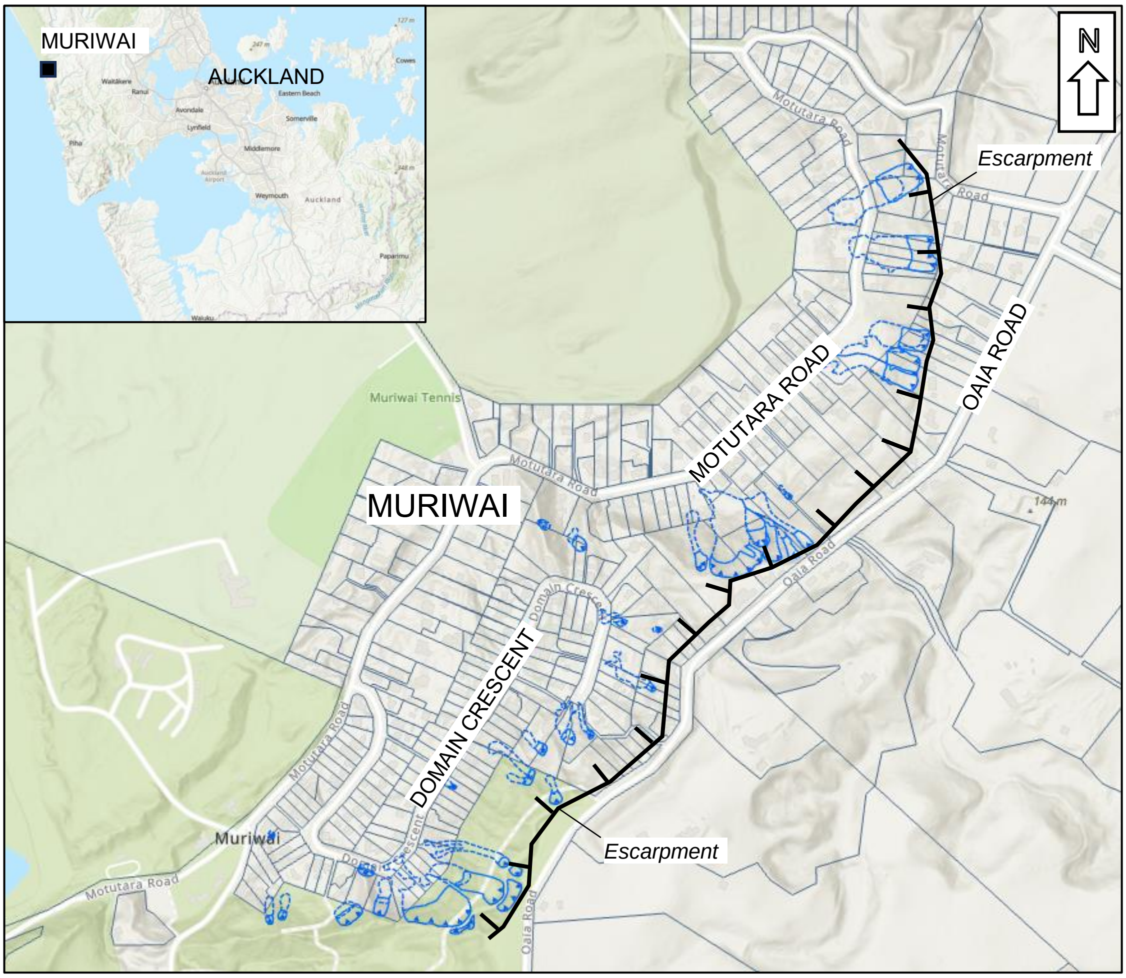


Figure 1 ***Muriwai location showing the February 2023 landslides mapped by GHD (blue lines)***

1.3 Scope

AC would like to understand the risk-to-life of large-scale[2,3] slope instability in the settlement of Muriwai to inform possible future dwelling hazard designations, including the revision of building placards issued in February 2023. Landslides from the main escarpment to the east of Muriwai that were associated with Cyclone Gabrielle have demonstrated that some dwellings are exposed to an unacceptably high landslide risk. AC may designate these properties as being unsuitable for habitation. The approach to inform such decisions must be robust and defensible. The scope for this study is as follows:

- Establish a ground surface GIS model using data provided by AC.
- Conduct an engineering geological assessment of the area to understand the physical contributary factors that led to recent large-scale landslides and that may provide insight into future events.
- Conduct a ground borehole investigation of Muriwai to understand the geological materials in the area. This includes laboratory testing of recovered soil and rock to characterise their geotechnical properties.
- Simulate the slope stability of the main escarpment using a Limit Equilibrium slope stability analysis to quantify the failure conditions and to provide indications of two potential remedial measures.
- Undertake a simulation of the potential for future debris flow from the escarpment using RAMMS computer software. The focus for this is to identify which dwellings could be affected by potentially damaging, life-threatening debris flows.

---

[2] In this report 'large scale' landslide hazards refers to landslides originating from the main escarpment that typically have a volume of more than about 50 m^3 with the potential to cause total or partial collapse of a dwelling.
[3] Some limited, site-specific assessments by GHD have been appended to this report (see Appendix E-2, E-3, E-4) that do assess the risk to specific properties. This reflects an evolution in the scope of GHD's service as requested by Auckland Council.

- Quantify the risk to life of residents from potential future debris flows using data from the above items, in particular the RAMMS output.

AC requested that this study be limited to the assessment of the effect from 'large scale' landslide hazards originating from the main escarpment located to the south-east of Muriwai because the initial placard assessment was largely aimed at mitigating risks associated with these landslide hazards. Consequently, this report does not consider smaller, more localised landslide hazards that could originate (or may have already initiated) from other areas in Muriwai such as within the footprint of individual residential properties. Separate site-specific risk assessments have been undertaken by GHD for several individual properties at AC's request to further clarify risk outcomes within the area-wide study. The results of these are not included in this report.

This report has been prepared by GHD for Auckland Council and may only be used and relied on by Auckland Council for the purpose agreed between GHD and Auckland Council as set out in section 1.1 of this report.

GHD otherwise disclaims responsibility to any person other than Auckland Council arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

1.4 Report structure and revision version

The appended reports and figures provide the detail and calculations of our study. This overall report provides a framework to combine this information and summarises the contents of each report. A draft version of this report was submitted to AC on 24 August 2023 and they used it to inform their provisional Risk Categorisation[4] assignment. The report and Risk Categorisation was released to the public shortly after.

A final (Revision 0) report was an updated version of the draft report that included completed geotechnical investigation and materials testing that was ongoing at the time of the draft release. The report also partially responded to comments from AC's technical peer review committee and from community feedback.

This report (Revision 1) is a further update that is considered to be complete, with no further additions intended. It addresses all outstanding comments from AC's technical peer review committee and community feedback. In most cases the structure of the appended reports is unchanged, but their content is supplemented with more detail, including some additional figures (e.g. figures A127-A129).

Excluded from this report is consideration of the risk relating to dwellings located along the crest of the main escarpment (i.e. the west side of Oaia Road) that could be undermined by the regression of the escarpment edge during future landslide events. Commentary on escarpment edge regression is to be included in a separate, future study.

A list of report sections is presented in Table 1. A3 plans referred to in this report are presented in Appendix A.

Table 1 Summary of accompanying Muriwai landslide risk assessment reports

Report Section	Description
Overall Report	*Waitakere Coastal Communities Landslide Risk Assessment (Muriwai) Overall Report (this report)*
Appendix A	Figures
Appendix B	Engineering Geological Report
Appendix C	Slope Stability Assessment
Appendix D	RAMMS debris flow analysis
Appendix E	Landslide Risk Assessment
Appendix F	Geotechnical Investigations Report

---

[4] For an explanation of Risk Categories, see Property risk categories (aucklandcouncil.govt.nz)

2. Assessment work stages

This section summarises the project work stages and outlines the main conclusions.

2.1 Engineering geological report (Appendix B)

The purpose of the engineering geological report was to assemble existing data and combine it with observations and anecdotal evidence from the community to inform a model for the area that provides the context for the observed landslides and helps to assess the nature of and triggers for future occurrences. This appendix report has been substantially updated from the draft version.

The following conclusions were reached in the engineering geological assessment of the Muriwai landslide hazard:

1. The recent (2023) and historical (1965) landslides that have affected the Muriwai community were high-velocity debris flows originating on the escarpment that extends up to 80 m above the township.
2. The model proposed for the recent (2023) and historical (1965) landslides that damaged the Muriwai community is that of saturated and shallow translational slips that quickly become high-velocity debris flows, entraining significant volumes of unconsolidated sand and vegetation.
3. The formation of these landslides can be directly attributed to the saturation of surficial soil (colluvium and weathered rock) in the Awhitu Sand Formation which, upon losing its binding iron-cement, develops a shallow shear surface.
4. This process is probably influenced by a combination of surface water infiltration and subsurface pore pressure increases from perched aquifers and associated springs. However, as no groundwater or overland flow data is available from during the events, reliance is placed on anecdotal accounts which do not provide a clear picture.
5. From the data available, including continuous groundwater monitoring established after the 2023 event, it is inferred that surface water flow and infiltration/saturation of shallow soils has had the greater effect on the onset of landslides.
6. The speed, composition, and volume of the debris generated make these debris flows highly destructive to dwellings and property located within the run-out area. As a result, tragically, multiple fatalities were experienced in both the 1965 and 2023 events.
7. The debris flows follow local catchment valleys which often coalesce multiple landslides into confined areas. Consequently, the location and degree of damage to residential properties is variable along Domain Crescent and Motutara Road.
8. Deep-seated landslides resulting from large (i.e. ARI 100 year) rain events within the study area (escarpment) and geology (Awhitu Formation) sand, are not considered likely. Although evidence that may be plausibly attributed to larger historical landslides has been observed, the relative magnitude of these features compared with the 2023 event suggests much larger, less frequent environmental conditions would be required to instigate failure (most likely a very large earthquake). Such conditions and resultant hazards have not been considered for this assessment.
9. Six geomorphological landslide ‘zones’ have been defined based on the surface topography, 2023 landslide characteristics and general geomorphology of the study area. These differentiate areas according to their susceptibility to large-scale landslides (i.e. having a volume of more than approximately 50 m^3). Zones 2, 3 and 4 contain the Muriwai escarpment and have higher potential for future, large landslides.
10. The life risk to residents for each zone is considered separately in the risk assessment (Appendix E).

Interactive community sessions held in September 2023 in Muriwai provided clarification to residents by GHD and AC following the release of the draft version of this report and associated appended reports. We received a large response from the community after the release of the draft report, with additional observations and suggested amendments to the anecdotal information presented below.

2.2 Slope stability assessment (Appendix C)

The purpose of this report was to present a slope stability and back analysis assessment of one of the large, failed slopes at the escarpment to the east of Muriwai township. The objective of the analyses was to estimate rock or soil strength parameters that could be used to inform conceptual remediation options to demonstrate the likely effectiveness of engineering measures that could be required to stabilise the escarpment.

Slope stability analyses were carried out using Slope W version 2021.3 (a GeoStudio Package). As part of the back analyses and feasibility assessments, we examined non-circular, shallow, deep circular and irregular user-defined slip surfaces.

A two-dimensional Limit Equilibrium Analysis was carried out to estimate material parameters applicable to the failed zone. The analysis also assessed the influence of changing pore pressure levels. The seismic performance of the slopes was also assessed, considering factors such as design life, site soil class, peak ground acceleration, and compliance with the NZ Building Code. Based on this, we considered two engineering options that would provide long-term stability to the escarpment: widespread soil nails and benching of the slope. These highlighted the high cost of slope remediation on this scale.

2.3 RAMMS debris flow analysis (Appendix D)

The purpose of this assessment was to present the results of a RAMMS computer-simulated three-dimensional debris flow assessment undertaken to provide guidance on the potential effects of future events on dwellings in Muriwai. In addition, a sensitivity analysis of input parameters is presented. The analysis focus is on the large-scale hazard from the 80 m-high escarpment to the east of Muriwai township that experienced damaging landslides in February 2023. The results from the analysis provide an important part of the GHD loss of life risk study (see Appendix E) that will support decision-making by AC on the long-term suitability of sites and dwellings for occupancy.

The RAMMS debris flow analysis used simulated landslides from source areas similar to those of the damaging February 2023 Cyclone Gabrielle, and from potential, future sources. Geomorphological Zone 5 landslides as described in Appendix B were used to calibrate specific parameters for RAMMS analysis due to the relatively short debris flow runout distance when compared to other zones.

We conclude the following:

1. A quantitative comparison of the actual landslide runout areas with that determined from RAMMS simulation indicates a reasonable fit.
2. The predicted outcome of the simulation is that over 40 originally red-placarded dwellings could be subjected to impact by escarpment landslide debris that is greater than 0.5 m thick as shown on Figures A206 and A209. This has been assessed by GHD's risk assessment in Appendix E as having the potential to cause fatalities, especially if large trees are mobilised by the landslide.
3. Yellow placarded properties are largely beyond the extent of the escarpment landslide debris that is greater than 0.5 m thick.
4. The RAMMS predicted runout extent of damaging debris (i.e. more than 0.5 m maximum thickness) is in broad agreement with the 'F-angle' empirical landslide hazard prediction work undertaken by AC to allocate the original emergency property placards.

2.4 Landslide risk assessment (Appendix E)

The purpose of this assessment was to present the results of a Quantitative Landslide Risk Assessment (QRA) carried out to estimate[5] the risk of loss of life posed by large-scale landslides to individuals in dwellings at Muriwai.

---

[5] QRA is a systematic method that integrates knowledge and uncertainty to identify and quantify risks. In a QRA the life risk is determined by a calculation but the result is called an estimate because of the inherent uncertainty.

It was carried out in general accordance with the Australian Geomechanics Society Practice Note Guidelines for Landslide Risk Management, commonly known as AGS (2007c). A “risk to property” assessment has not been undertaken.

Occupants of dwellings that have been assessed to be in the path of landslide runout were considered as the elements at risk for this assessment. The risks posed to individuals in the ‘open’, such as people outside houses or situated on other public property such as roads, are not considered in this report. The ‘tolerable’ level of loss-of-life risk in AGS (2007c) is 10^{-4} per annum, which is the same as 1 in 10,000 fatalities pa.

The assessment considers the risk within the six geomorphological landslide ‘zones’ that have been introduced in Appendix B. The risk assessment relied on the outputs of the RAMMS modelling in Appendix D as the basis for determining areas of the site that could be affected by landsliding.

Where RAMMS predicts debris flow of greater than 0.5 m depth, the greatest present estimated risk to life (climate change not considered) is as follows:

- For Zone 1 the risk is ‘tolerable’.
- For Zone 2 the risk is ‘not tolerable’.
- For Zone 3 the risk is ‘not tolerable’.
- For Zone 4 the risk is ‘not tolerable’.
- For Zone 5 the risk is ‘not tolerable’.
- For Zone 6 the risk is ‘tolerable’.

The risks are judged ‘acceptable’ or ‘tolerable’ where the depth of the debris flow is less than 0.5 m.

2.5 Geotechnical investigations report (Appendix F)

The purpose of this report is to present data from a geotechnical borehole investigation and groundwater monitoring programme that was conducted as part of the landslide study. This report is a factual account of the work undertaken, the materials that were encountered and their geotechnical characterisation from laboratory testing. These results are used to inform the engineering geological characterisation in Appendix B.

Work undertaken was as follows:

Boreholes

- Nine cored boreholes advanced to a depth of between 11 m and 80 m below ground level (bgl) at locations at the top and below the escarpment, with the following distribution:
  - Three approximately 80 m deep boreholes at Oaia Road, east of (above) the Muriwai escarpment
  - Three boreholes below the Muriwai escarpment on Domain Crescent (two to approximately 11 m bgl and one to approximately 41 m bgl)
  - Three boreholes below the Muriwai escarpment on Motutara Road (two to approximately 11 m bgl and one to approximately 41 m bgl)
- Log the recovered material using NZGS (2005) guidelines
- Conduct Standard Penetration Tests (SPTs) at 1.5 m intervals
- Record data in AGS4 format and upload borehole logs to the New Zealand Geotechnical Database

Groundwater monitoring

- Install standpipe piezometer screens in some of the boreholes
- Measure initial water levels during drilling and following screen installation
- Supervise installation of water level data recorders and AC monitoring-compatible telemetry hardware to allow ongoing data collection (by AC)

Laboratory testing

- Testing of recovered soils and rocks including:

- Atterberg Limit testing
- Particle size distribution (wet sieve) tests
- Unconfined Compressive Strength tests
- Pinhole and Crumb dispersibility

This report may be updated in the future to include ongoing data.

3. Limitations

This report has been prepared by GHD Limited (GHD) for Auckland Council and may only be used and relied on by Auckland Council for the purpose agreed between GHD and Auckland Council as set out in Section 1 of this report.

GHD otherwise disclaims responsibility to any person other than Auckland Council arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

The opinions, conclusions and any recommendations in this report are based on assumptions made by GHD described in this report (refer Section 1 of this report). GHD disclaims liability arising from any of the assumptions being incorrect.

An understanding of the geotechnical site conditions depends on the integration of many pieces of information, some regional, some site specific, some structure specific and some experienced based. Hence this report should not be altered, amended, abbreviated, or issued in part in any way without prior written approval by GHD. GHD does not accept liability in connection with the issuing of an unapproved or modified version of this report.

Verification of the geotechnical assumptions and/or model is an integral part of the design process - investigation, construction verification, and performance monitoring. If the revealed ground or groundwater conditions vary from those assumed or described in this report the matter should be referred back to GHD.

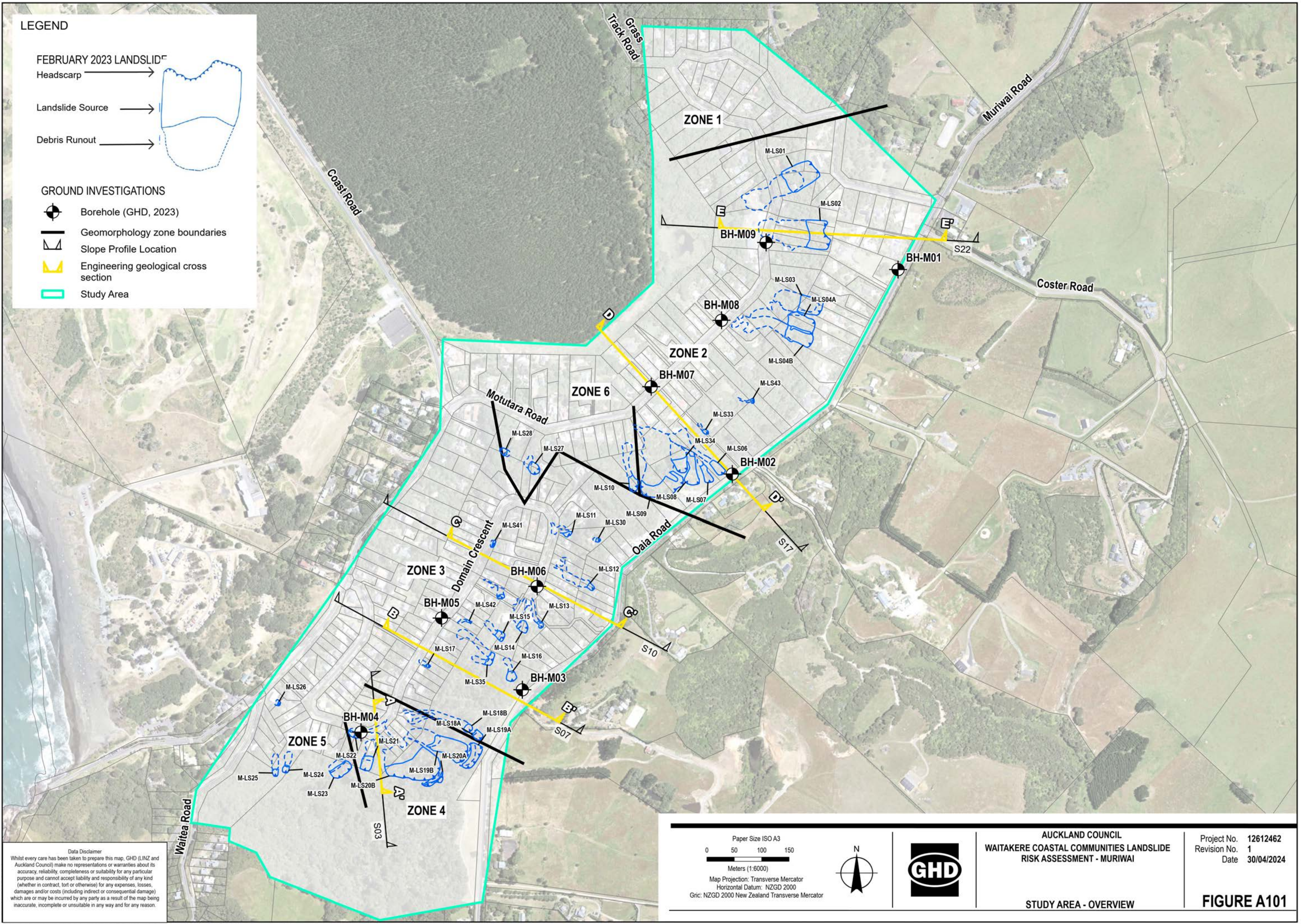
Appendices

Appendix A

Figures

Table 2 Project A3-size figures

Figure No.	Description
GENERAL SITE LAYOUT	
A101	OVERVIEW
ENGINEERING GEOLOGICAL PLANS	
A111	LEGEND
A112	OVERVIEW
A113 -A116	CLOSE-UP PLANS
CROSS SECTIONS	
A120	CROSS SECTION A-A’
A121	CROSS SECTION B-B’
A122	CROSS SECTION C-C’
A123	CROSS SECTION D-D’
A124	CROSS SECTION E-E’
GEOMORPHOLOGICAL LANDSLIDE ZONES	
A125	SLOPE RELIEF AND PROFILE COMPARISON PLAN
ELEVATION MODEL COMPARISON	
A126	ELEVATION COMPARISON BETWEEN 2016 AND 2023 LiDAR TOPOGRAPHIC SURVEYS
SLIP MECHANISM MODEL	
A127	2023 CYCLONE GABRIELLE LANDSLIDE MECHANISM MODEL, MURIWAI
A128	2023 CYCLONE GABRIELLE LANDSLIDE MECHANISM MODEL - PHOTO MARK-UP
RAMMS DEBRIS FLOW SIMULATION PLANS	
A201	MAXIMUM DEBRIS HEIGHT EXTENTS FOR BEST CASE, PREDICTED AND WORST CASE SCENARIOS - (GREATER THAN 0.01 M DEEP) - OVERVIEW
A202	PREDICTED MAXIMUM DEBRIS HEIGHT (GREATER THAN 0.01 M DEEP) - OVERVIEW
A203 - A205	PREDICTED MAXIMUM DEBRIS HEIGHT (GREATER THAN 0.01 M DEEP) - CLOSE-UP
A206	MAXIMUM DEBRIS HEIGHT EXTENTS (GREATER THAN 0.5 M DEEP) - OVERVIEW
A207 - A209	MAXIMUM DEBRIS HEIGHT EXTENTS (GREATER THAN 0.5 M DEEP) - CLOSE-UP



Map Projection: Transverse Mercator
Horizontal Datum: NZGD 2000
Gric: NZGD 2000 New Zealand Transverse Mercator

AUCKLAND COUNCIL
WAITAKERE COASTAL COMMUNITIES LANDSLIDE RISK ASSESSMENT - MURIWAI

STUDY AREA - OVERVIEW

Project No.	**12612462**
Revision No.	**1**
Date	**30/04/2024**

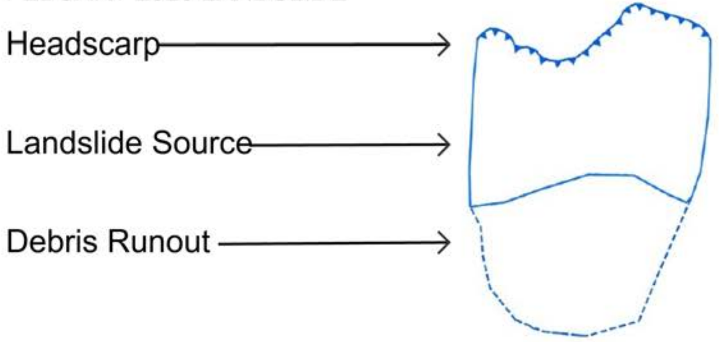
FIGURE A101

\\ghdnet\ghd\NZ\Auckland\Projects\51\12612462\GIS\Maps\Working\12612462_Geotech_Muriwai_AppA.aprx
Print date: 26 Apr 2024 - 12:52

Data source: World Imagery: Auckland Council, Maxar; LINZ- Parcel, Road,GHD- Anecdotal evidence, Landslide Extend, Site extend - 20230811. Created by: nrama

GEOMORPHOLOGICAL FEATURES

FEBUARY 2023 LANDSLIDE



- GNS Mapped Fault
- Lineament
- Mid-Slope Bench
- Break in slope
- Ridge lines
- Valley
- Water/Stream/Overland Flow Path
- ▨ Reservoir
- Mapped Spring

GEOLOGICAL UNITS

KAIHU GROUP	Mitiwai Sand Formation (qm/qmf)	0 - 0.014 MYA
	Nominal Extent of Ancient Colluvium (qhc)	0 - 0.07 MYA
	Less Cemented Awhitu Sand Formation (qsu)	0.07 - 3.5 MYA
	More Cemented Awhitu Sand Formation (qsc)*	0.07 - 3.5 MYA
EROSIONAL UNCONFORMITY		
WAITAKERE GROUP	Tirikoha Formation (mt)	16 - 17 MYA
	Waiatarua Formation (mw)	16 - 19 MYA
	Nihotupu Formation (mn)	17 - 21 MYA

* Not visible at ground surface - refer to cross sections (A120 - A124)

MISCELLANEOUS

- Borehole (GHD, 2023)
- Indicative Strike and Dip of the Nihotupu Formation
- Engineering geological cross section
- Slope Profile Location
- Contour (10m)
- Contour (5m)
- Contour (1m)
- Geomorphology zone boundaries
- ▲ Edwin Mitchelson Face Log
- Edwin Mitchelson track
- ▨ Historic landslide (1965)

ANECDOTAL EVIDENCE

- Depression
- Drain
- Landslide
- Retaining Wall
- Anecdotal Spring
- Stream

\\ghdnet\ghd\NZ\Auckland\Projects\51\12612462\GIS\Maps\Working\12612462_Geotech_Muriwai_AppA.aprx
Print date: 24 Apr 2024 - 17:52

Data source: ; LINZ- Parcel, Road. Auckland Council - Address/Housing number, GHD- Site extend - 20230811, differences in pre and post topography model (by GHD) - 20230811. Created by: nrama

Paper Size ISO A3

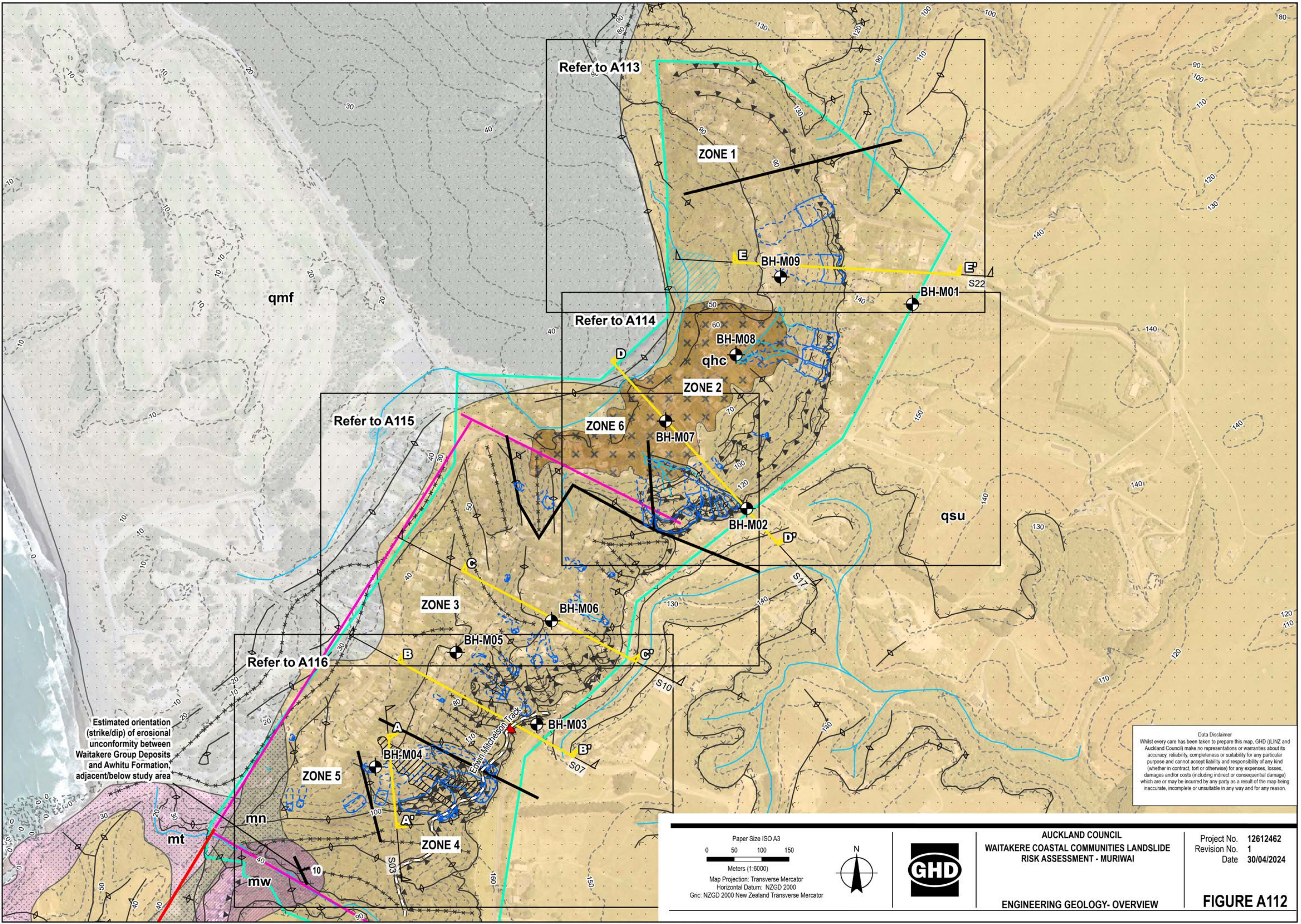
GHD

AUCKLAND COUNCIL
WAITAKERE COASTAL COMMUNITIES LANDSLIDE RISK ASSESSMENT - MURIWAI

ENGINEERING GEOLOGY - LEGEND

Project No. **12612462**
Revision No. **1**
Date **30/04/2024**

FIGURE A111



Data Disclaimer

Paper Size ISO A3

0 50 100 150

Meters (1:6000)

Map Projection: Transverse Mercator
Horizontal Datum: NZGD 2000
Gric: NZGD 2000 New Zealand Transverse Mercator

AUCKLAND COUNCIL
WAITAKERE COASTAL COMMUNITIES LANDSLIDE
RISK ASSESSMENT - MURIWAI

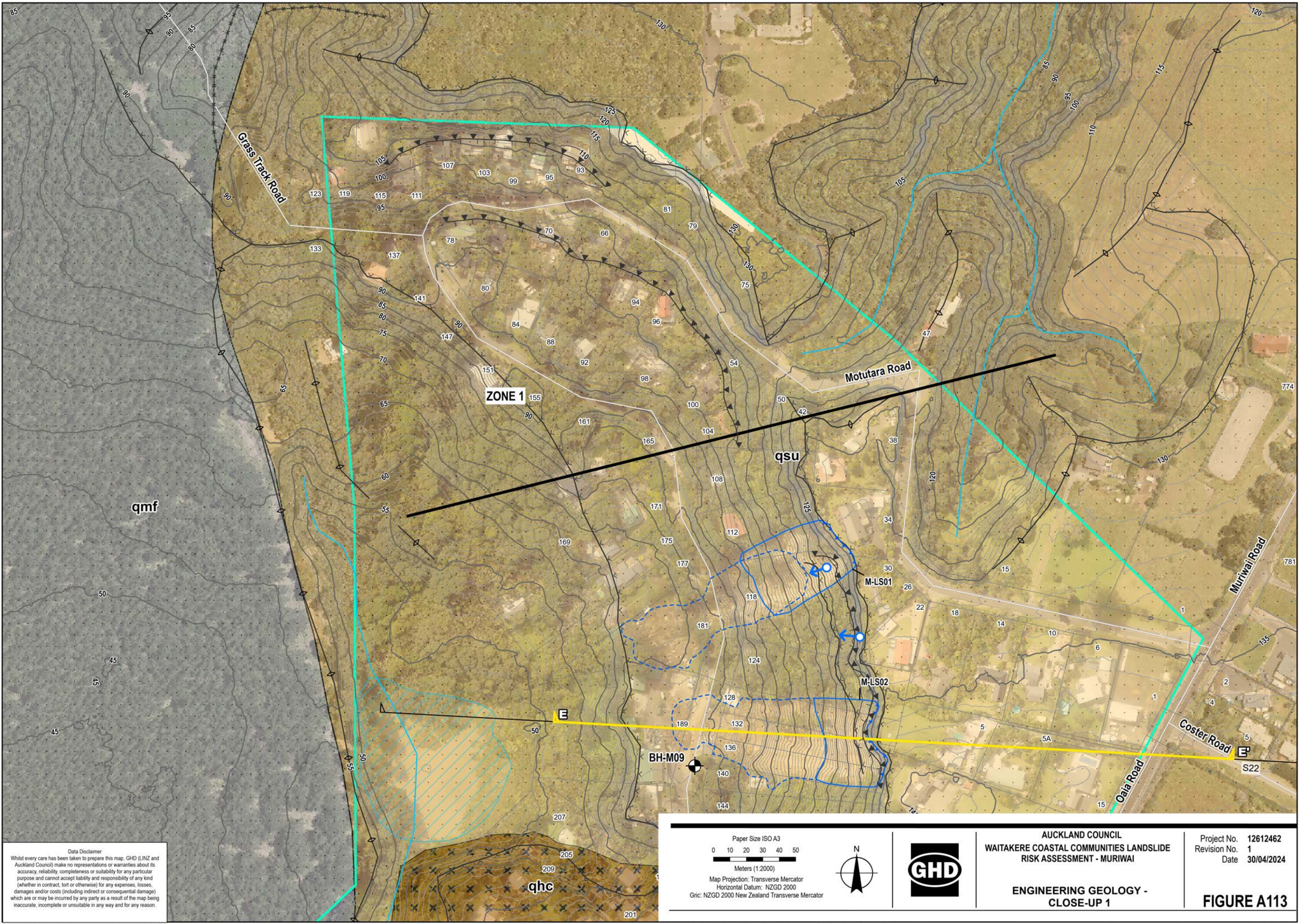
ENGINEERING GEOLOGY- OVERVIEW

Project No.	12612462
Revision No.	1
Date	30/04/2024

FIGURE A112

\\ghdnet\ghd\NZ\Auckland\Projects\51\12612462\GIS\Maps\Working\12612462_Geotech_Muriwai_AppA.aprx
Print date: 24 Apr 2024 - 18:30

Data source: World Imagery: Auckland Council, Maxar; LINZ- Parcel, Road. Auckland Council - Address/Housing number, placard status; GHD - Landslide, Watercourse, Machine Boreholes, inferred faults, Cemented Benches, Structural and geomorphological features, Edwin Mitchelson Face Log, Cross section, reservoirs, Map grid, Site extend -20230811. GNS - Geology units. Created by: nrama



Paper Size ISO A3
0 10 20 30 40 50
Meters (1:2000)
Map Projection: Transverse Mercator
Horizontal Datum: NZGD 2000
Gric: NZGD 2000 New Zealand Transverse Mercator

AUCKLAND COUNCIL
WAITAKERE COASTAL COMMUNITIES LANDSLIDE RISK ASSESSMENT - MURIWAI

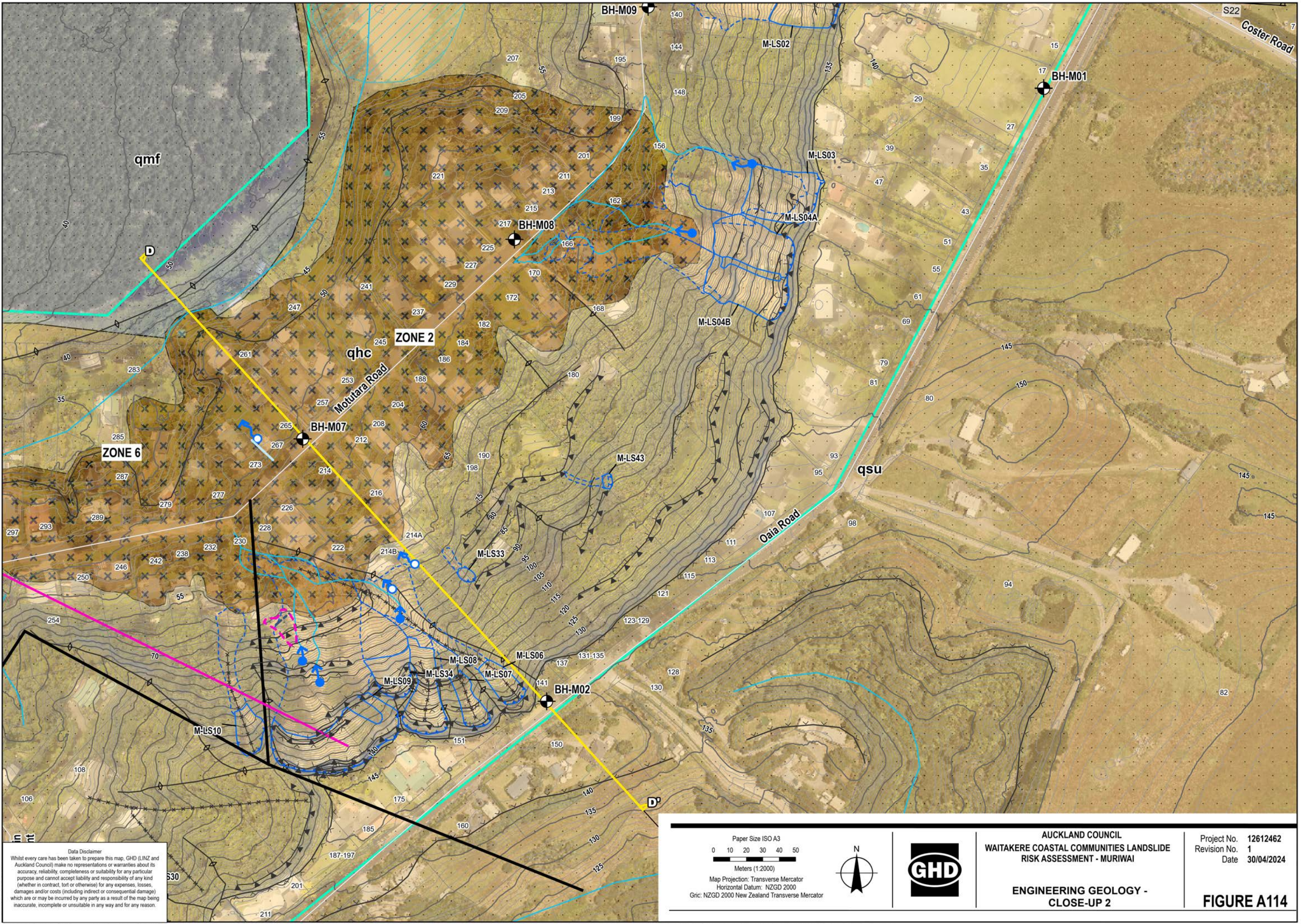
ENGINEERING GEOLOGY - CLOSE-UP 1

Project No.	12612462
Revision No.	1
Date	30/04/2024

FIGURE A113

Data source: NZ - Imagery: Eagle Technology, Land Information New Zealand, GEBCO, Community maps contributors; LINZ- Parcel, Road. Auckland Council - Address/Housing number, placard status; GHD - Field map points, Landslide, Watercourse, Machine Boreholes, inferred faults, cemented Benches, structural and geomorphological features, Edwin Mitchelsor Face Log, cross section, reservoirs Site extend -20230811. GNS - Geology units. Created by: nrama

\\ghdnet\ghd\NZ\Auckland\Projects\51\12612462\GIS\Maps\Working\12612462_Geotech_Muriwai_AppA.aprx
Print date: 24 Apr 2024 - 18:36



Paper Size ISO A3

0 10 20 30 40 50

Meters (1:2000)

Map Projection: Transverse Mercator
Horizontal Datum: NZGD 2000
Gric: NZGD 2000 New Zealand Transverse Mercator

N

GHD

AUCKLAND COUNCIL
WAITAKERE COASTAL COMMUNITIES LANDSLIDE
RISK ASSESSMENT - MURIWAI

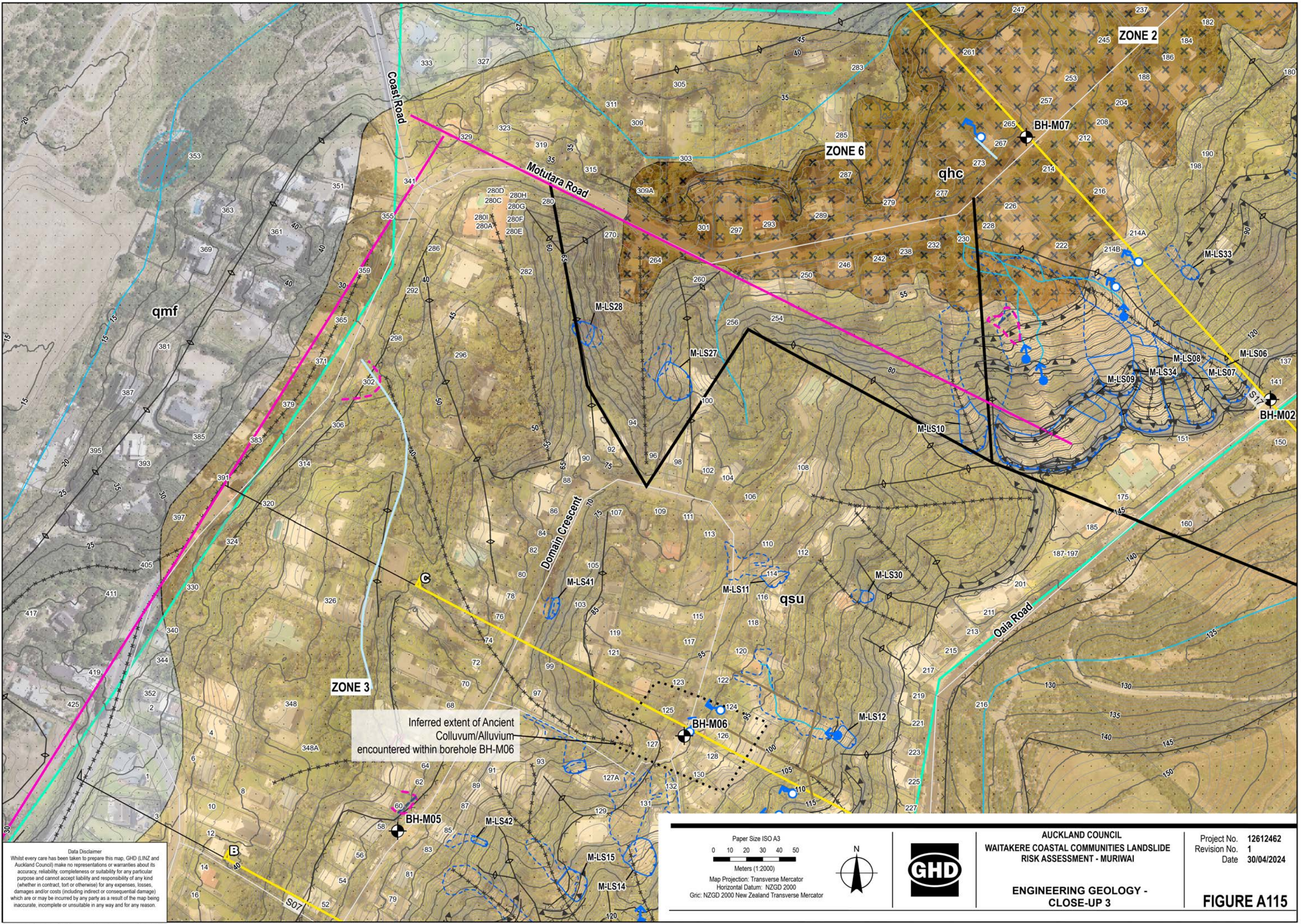
ENGINEERING GEOLOGY -
CLOSE-UP 2

Project No.	12612462
Revision No.	1
Date	30/04/2024

FIGURE A114

\\ghdnet\ghd\NZ\Auckland\Projects\51\12612462\GIS\Maps\Working\12612462_Geotech_Murawai_AppA.aprx
Print date: 24 Apr 2024 - 18:37

Data source: NZ - Imagery: Eagle Technology, Land Information New Zealand, GEBCO, Community maps contributors; LINZ- Parcel, Road. Auckland Council - Address/Housing number, placard status; GHD - Field map points, Landslide, Watercourse, Machine Boreholes, inferred faults, cemented Benches, structural and geomorphological features, Edwin Mitchelsor Face Log, cross section, reservoirs Site extend -20230811. GNS - Geology units. Created by: nrama



Paper Size ISO A3

0 10 20 30 40 50

Meters (1:2000)

Map Projection: Transverse Mercator
Horizontal Datum: NZGD 2000
Grid: NZGD 2000 New Zealand Transverse Mercator

N

AUCKLAND COUNCIL
WAITAKERE COASTAL COMMUNITIES LANDSLIDE RISK ASSESSMENT - MURIWAI

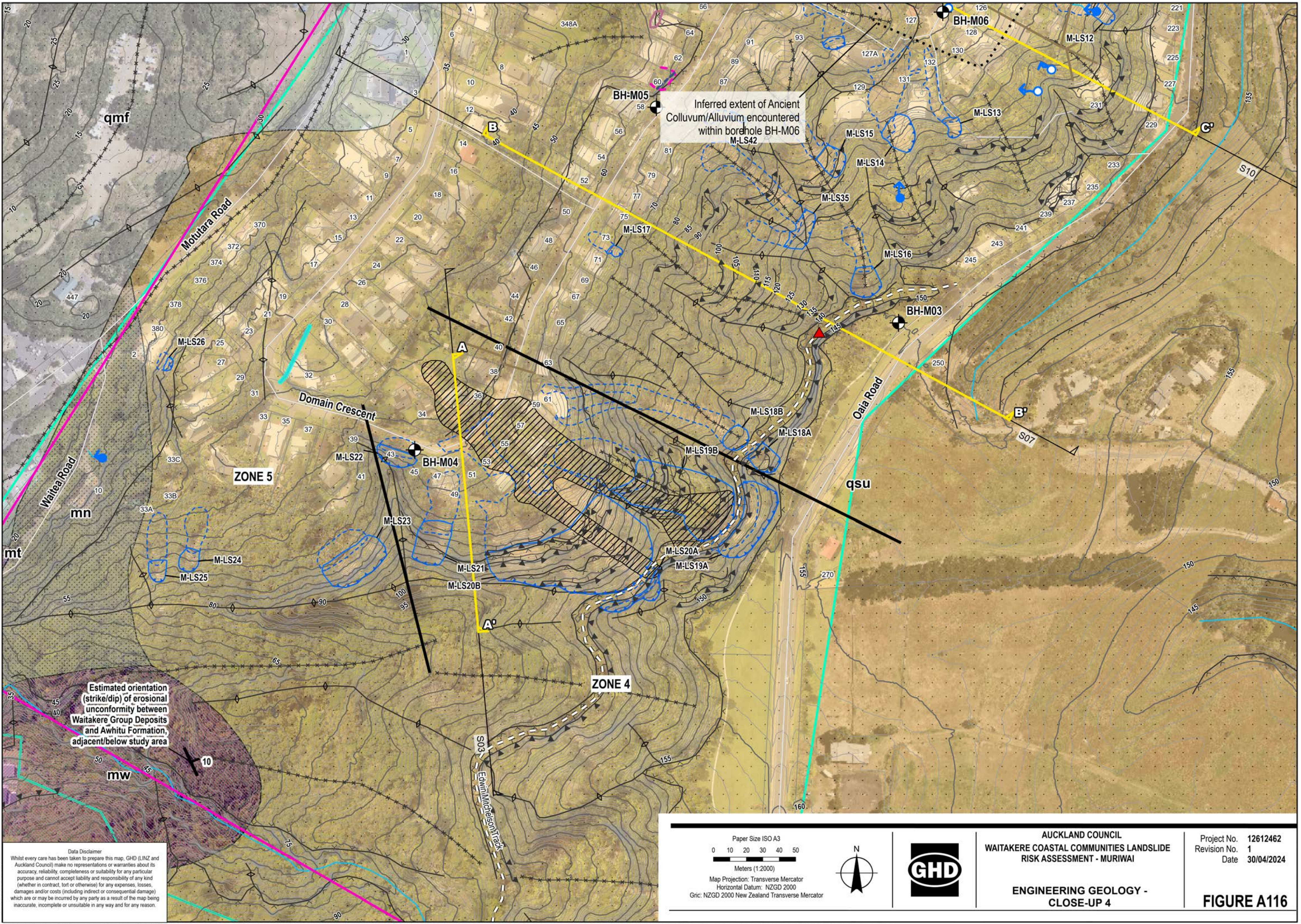
ENGINEERING GEOLOGY -
CLOSE-UP 3

Project No.	12612462
Revision No.	1
Date	30/04/2024

FIGURE A115

\\ghdnet\ghd\NZ\Auckland\Projects\51\12612462\GIS\Maps\Working\12612462_Geotech_Muriwai_AppA.aprx
Print date: 24 Apr 2024 - 18:38

Data source: NZ - Imagery: Eagle Technology, Land Information New Zealand, GEBCO, Community maps contributors; LINZ- Parcel, Road. Auckland Council - Address/Housing number, placard status; GHD - Field map points, Landslide, Watercourse, Machine Boreholes, inferred faults, cemented Benches, structural and geomorphological features, Edwin Mitchelsor Face Log, cross section, reservoirs Site extend -20230811. GNS - Geology units. Created by: nrama



Map Projection: Transverse Mercator
Horizontal Datum: NZGD 2000
Gric: NZGD 2000 New Zealand Transverse Mercator

AUCKLAND COUNCIL
WAITAKERE COASTAL COMMUNITIES LANDSLIDE RISK ASSESSMENT - MURIWAI

ENGINEERING GEOLOGY - CLOSE-UP 4

Project No.	12612462
Revision No.	1
Date	30/04/2024

FIGURE A116

Data source: NZ - Imagery: Eagle Technology, Land Information New Zealand, GEBCO, Community maps contributors; LINZ- Parcel, Road. Auckland Council - Address/Housing number, placard status; GHD - Field map points, Landslide, Watercourse, Machine Boreholes, inferred faults, cemented Benches, structural and geomorphological features, Edwin Mitchelsor Face Log, cross section, reservoirs Site extend -20230811. GNS - Geology units. Created by: nrama

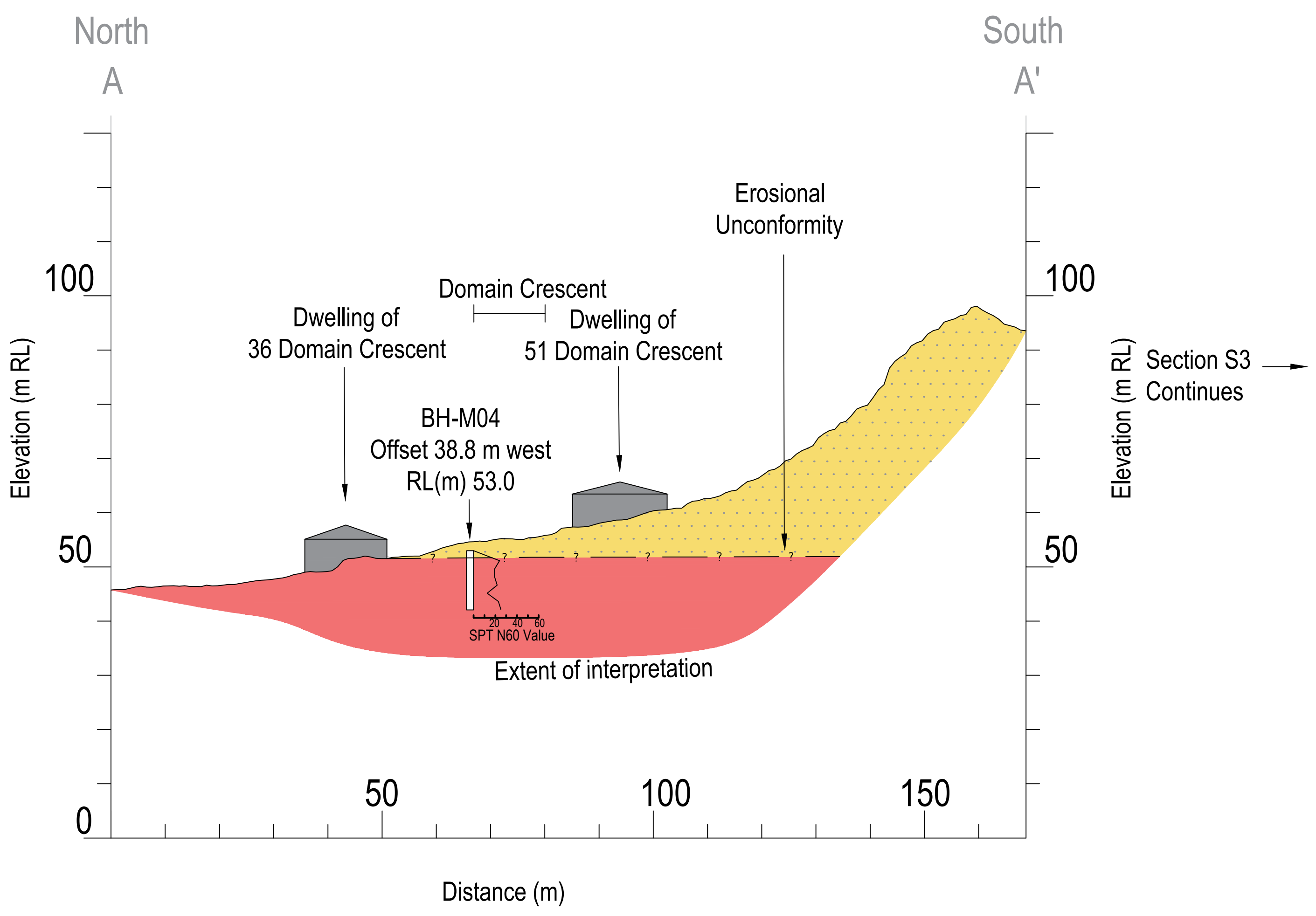
\\ghdnet\ghd\NZ\Auckland\Projects\51\12612462\GIS\Maps\Working\12612462_Geotech_Muriwai_AppA.aprx
Print date: 24 Apr 2024 - 18:40

LEGEND

▨	FILL
🟧	RECENT COLLUVIUM - POST-2023 LANDSLIDE EVENTS
🟨	INFERRED ANCIENT HISTORICAL COLLUVIAL/ALLUVIAL DEPOSITS
▩	MITIWAI SAND FORMATION: AEOLIAN DUNE SANDS
🟫	AWHITU SAND FORMATION: SILT/CLAY*
⬛	AWHITU SAND FORMATION: ORGANIC SOIL/PEAT*
▒	AWHITU SAND FORMATION: WEAKLY CEMENTED SAND SPT = <50
🟨	AWHITU SAND FORMATION: CEMENTED SAND SPT = 50+
🟥	NIHOTUPU FORMATION: SILT/CLAY
—·—	INFERRED GEOLOGICAL UNIT BOUNDARY
▯	BOREHOLE TRACE

NOTES

VERTICAL AND HORIZONTAL SCALE - 1:1
DEPTH OF LESS CEMENTED AWHITU SAND FORMATION INFERRED FROM BOREHOLE DATA AND APPROXIMATED TO TOPOGRAPHICAL SURFACE
NO PIEZOMETER CONSTRUCTED WITHIN BH-M04



01	FOR ILLUSTRATION	30/04/2024
Rev	**Description**	**Date**

Level 3, GHD Centre
27 Napier Street, Freemans Bay
Auckland 1011 New Zealand
T 64 9 370 8000 **F** 64 9 370 8001
E aklmail@ghd.com **W** www.ghd.com

www.ghd.com

GHD Limited

Project No. 12612462

Client AUCKLAND COUNCIL

Project WAITAKERE COASTAL COMMUNITIES
LANDSLIDE RISK ASSESSMENT - MURIWAI

Status FINAL

Status Code S4

Drawing Title MURIWAI CROSS SECTIONS
CROSS SECTION A-A' (S3)

Size A1

Drawing No. APPENDIX A120

Rev 01

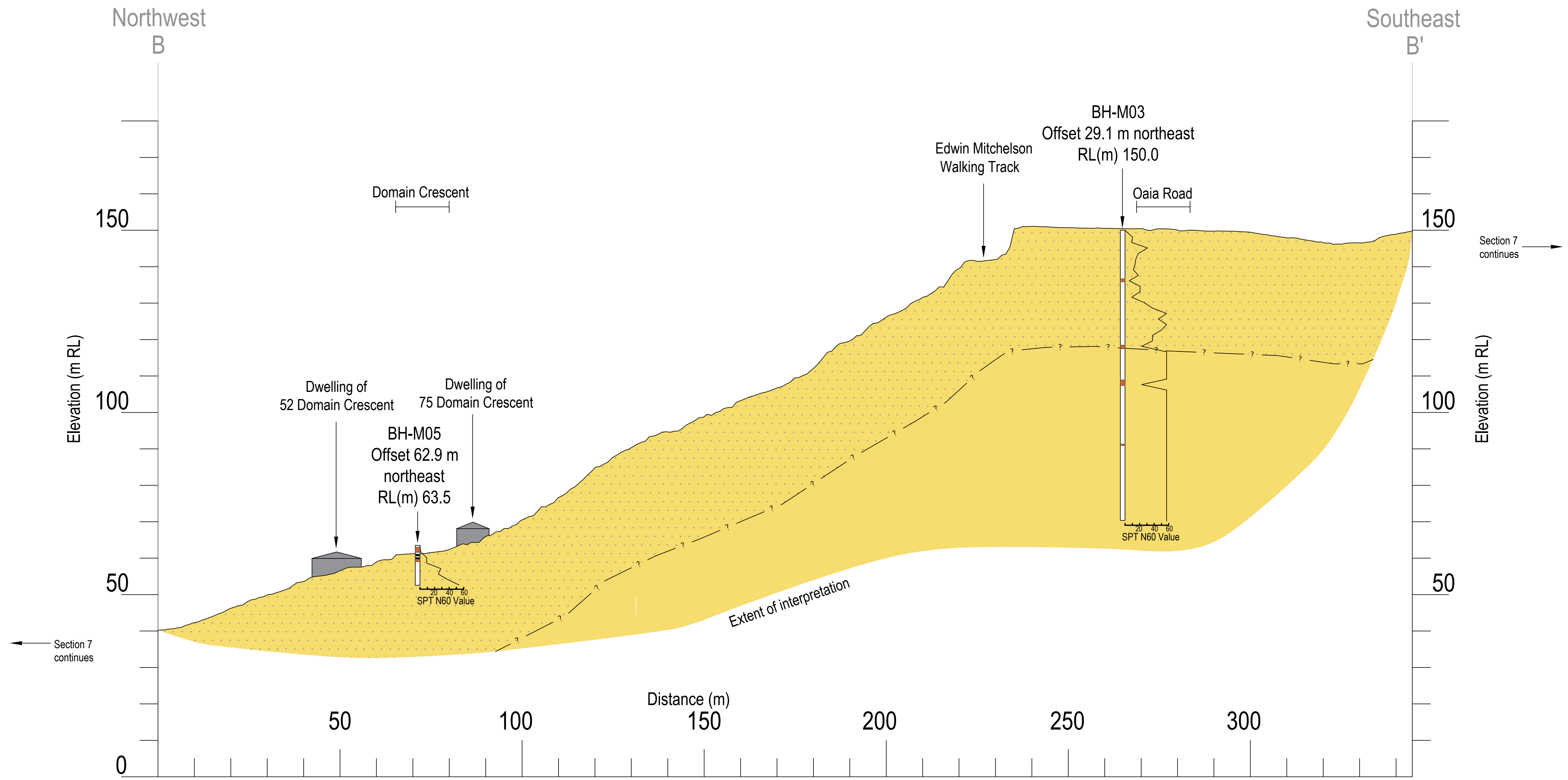
Plot Date: 29 April 2024 - 1:28 pm Plotted by: Luke Agnew File Name: N:\NZ\Auckland\Projects\51\12612462\04 GHD Working\22 Muriwai Cross Sections\02 Section lines\Section 3\12612462_GEOT_DRAWING - Section 3.dwg

LEGEND

▦ FILL
🟧 RECENT COLLUVIUM - POST-2023 LANDSLIDE EVENTS
🟨 INFERRED ANCIENT HISTORICAL COLLUVIAL/ALLUVIAL DEPOSITS
▩ MITIWAI SAND FORMATION: AEOLIAN DUNE SANDS
🟫 AWHITU SAND FORMATION: SILT/CLAY*
■ AWHITU SAND FORMATION: ORGANIC SOIL/PEAT*
▨ AWHITU SAND FORMATION: LESS CEMENTED SAND SPT = <50
🟨 AWHITU SAND FORMATION: MORE CEMENTED SAND SPT = 50+
🟥 NIHOTUPU FORMATION: SILT/CLAY
— ? — INFERRED GEOLOGICAL UNIT BOUNDARY
▯ BOREHOLE TRACE

NOTES

VERTICAL AND HORIZONTAL SCALE - 1:1
DEPTH OF LESS CEMENTED AWHITU SAND FORMATION INFERRED FROM BOREHOLE DATA AND APPROXIMATED TO TOPOGRAPHICAL SURFACE
NO PIEZOMETER CONSTRUCTED WITHIN BH-M05
FOR THE DATE RANGE BEING REPORTED (19/10/23 - 22/03/24) BH-M03 HAS BEEN MEASURED AS DRY



01	FOR ILLUSTRATION	30/04/2024
Rev	Description	Date

GHD
Level 3, GHD Centre
27 Napier Street, Freemans Bay
Auckland 1011 New Zealand
T 64 9 370 8000 **F** 64 9 370 8001
E aklmail@ghd.com **W** www.ghd.com

www.ghd.com

GHD Limited

Project No.
12612462

Client AUCKLAND COUNCIL

Project WAITAKERE COASTAL COMMUNITIES
LANDSLIDE RISK ASSESSMENT - MURIWAI

Status FINAL
Status Code S4

Drawing Title MURIWAI CROSS SECTIONS
CROSS SECTION B-B' (S7)

Size A1

Drawing No. APPENDIX A121

Rev 01

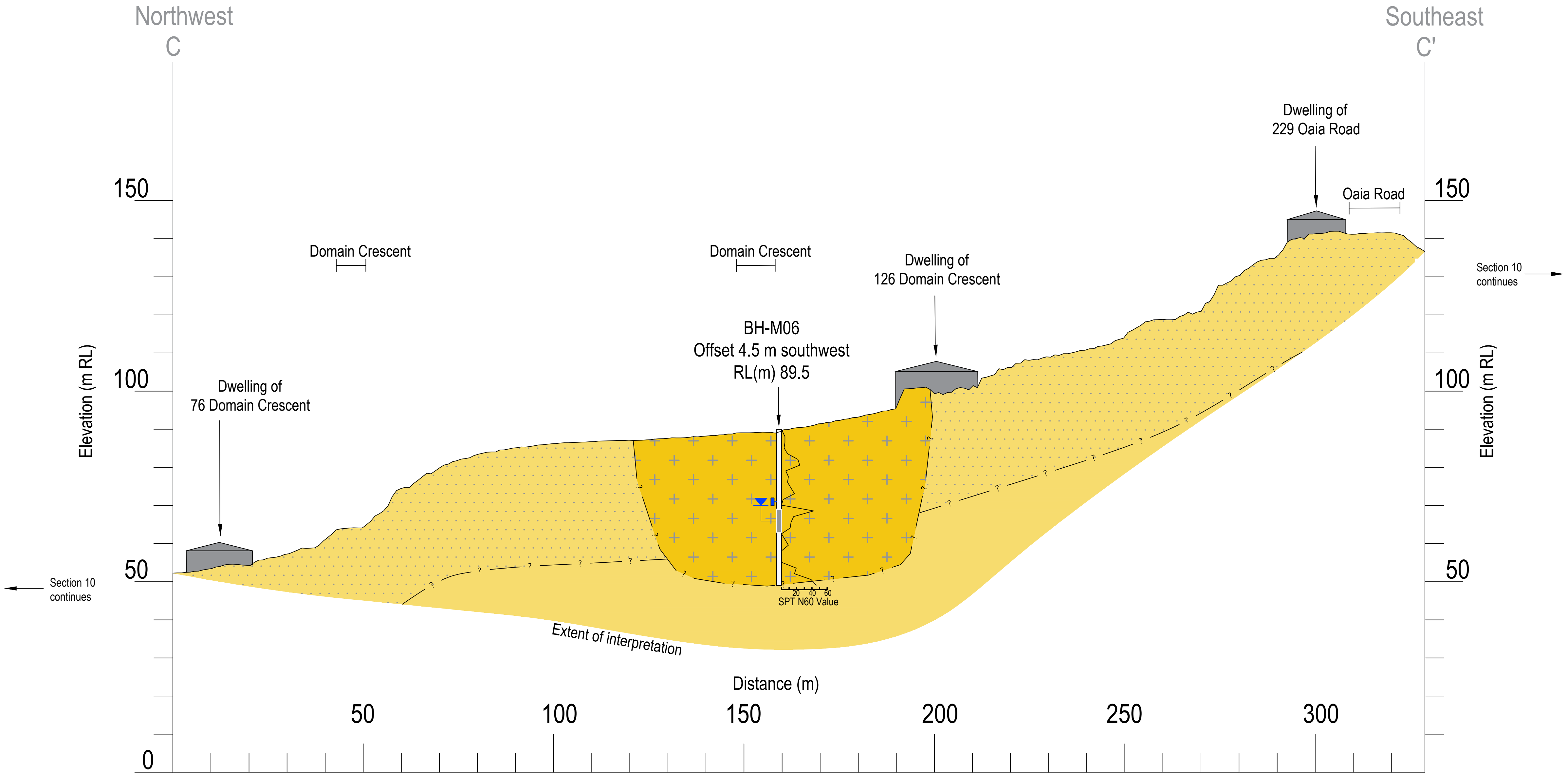
Plot Date: 29 April 2024 - 1:30 pm
Plotted by: Luke Agnew
File Name: N:\NZ\Auckland\Projects\51\12612462\04 GHD Working\22 Muriwai Cross Sections\02 Section lines\Section 7\12612462_GEOT_DRAWING - Section 7.dwg

LEGEND

- ▨ FILL
- 🟧 RECENT COLLUVIUM - POST-2023 LANDSLIDE EVENTS
- 🟨 INFERRED ANCIENT HISTORICAL COLLUVIAL/ALLUVIAL DEPOSITS
- ▨ MITIWAI SAND FORMATION: AEOLIAN DUNE SANDS
- 🟫 AWHITU SAND FORMATION: SILT/CLAY*
- ■ AWHITU SAND FORMATION: ORGANIC SOIL/PEAT*
- ▨ AWHITU SAND FORMATION: LESS CEMENTED SAND SPT = <50
- 🟨 AWHITU SAND FORMATION: MORE CEMENTED SAND SPT = 50+
- 🟥 NIHOTUPU FORMATION: SILT/CLAY
- INFERRED GEOLOGICAL UNIT BOUNDARY
- BOREHOLE TRACE
- MEASURED GROUNDWATER DIP 28/08/2023 - 29/08/2023
- RANGE IN TELEMETERED GROUNDWATER DATA 19/10/2023 - 22/03/2024
- PIEZOMETER SCREEN DEPTH

NOTES

VERTICAL AND HORIZONTAL SCALE - 1:1
BH-M06 - INFERRED ANCIENT HISTORICAL COLLUVIAL/ALLUVIAL DEPOSITS - UNKNOWN LATERAL EXTENT
DEPTH OF LESS CEMENTED AWHITU SAND FORMATION INFERRED FROM BOREHOLE DATA AND APPROXIMATED TO TOPOGRAPHICAL SURFACE
FOR FURTHER DISCUSSION ON THE ANCIENT COLLUVIUM/ALLUVIUM PLEASE SEE SECTION 4.3 IN APPENDIX B
LIMITED INVESTIGATION DATA AVAILABLE, AS SUCH GROUNDWATER SURFACE HAS NOT BEEN INTERPOLATED BETWEEN BOREHOLES



Rev	Description	Date
01	FOR ILLUSTRATION	30/04/24

GHD

Level 3, GHD Centre
27 Napier Street, Freemans Bay
Auckland 1011 New Zealand
T 64 9 370 8000 **F** 64 9 370 8001
E aklmail@ghd.com **W** www.ghd.com

www.ghd.com

GHD Limited

Project No. 12576144

Client AUCKLAND COUNCIL

Project WAITAKERE COASTAL COMMUNITIES LANDSLIDE RISK ASSESSMENT - MURIWAI

Status FINAL

Status Code S4

Drawing Title MURIWAI CROSS SECTIONS
SECTION C-C' (S10)

Size A1

Drawing No. APPENDIX A122

Rev 01

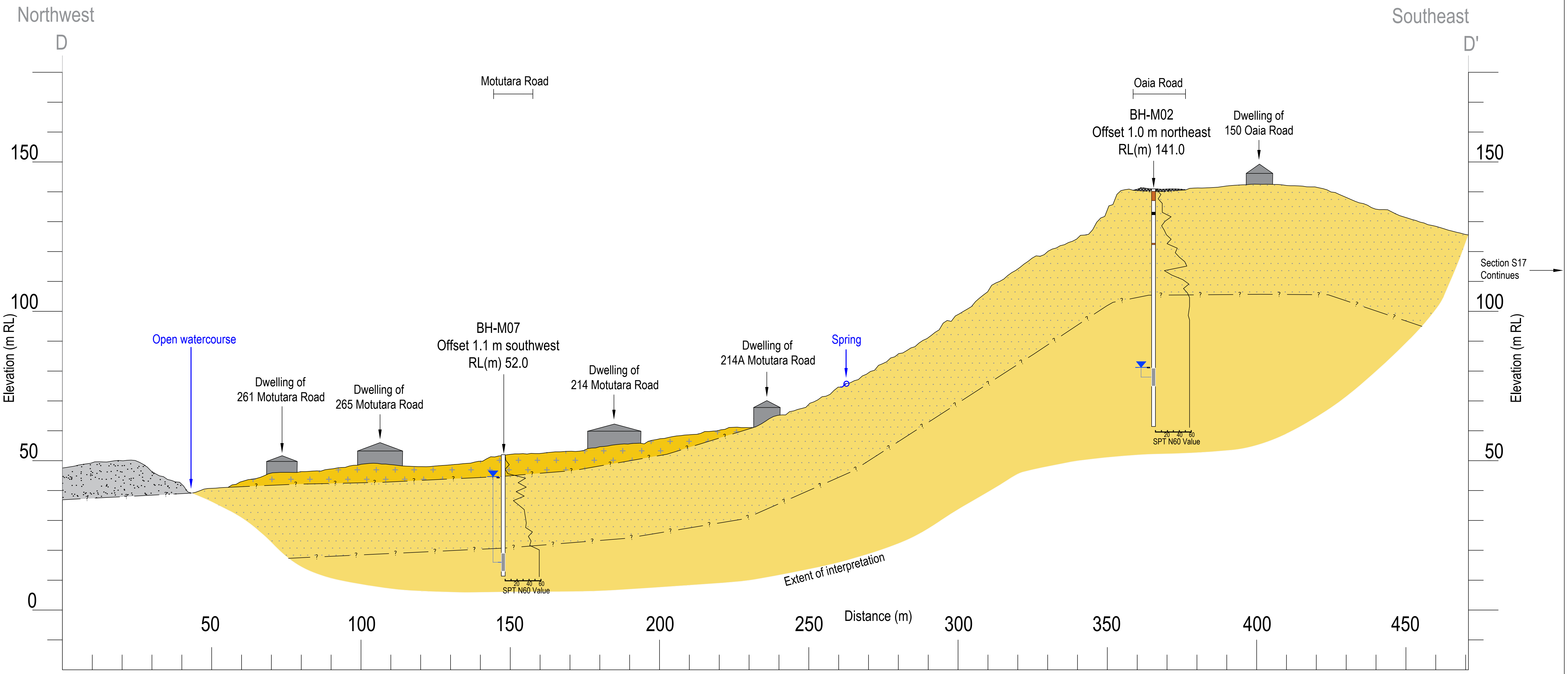
Plot Date: 24 April 2024 - 5:43 pm   Plotted by: Luke Agnew   File Name: N:\NZ\Auckland\Projects\51\12612462\04 GHD Working\22 Muriwai Cross Sections\02 Section lines\Section 10\12612462_GEOT_DRAWING - Section 10.dwg

LEGEND

- ▨ FILL
- ▨ RECENT COLLUVIUM - POST-2023 LANDSLIDE EVENTS
- ▨ INFERRED ANCIENT HISTORICAL COLLUVIAL/ALLUVIAL DEPOSITS
- ▨ MITIWAI SAND FORMATION: AEOLIAN DUNE SANDS
- ■ AWHITU SAND FORMATION: SILT/CLAY*
- ■ AWHITU SAND FORMATION: ORGANIC SOIL/PEAT*
- ▨ AWHITU SAND FORMATION: LESS CEMENTED SAND SPT = <50
- ■ AWHITU SAND FORMATION: MORE CEMENTED SAND SPT = 50+
- ■ NIHOTUPU FORMATION: SILT/CLAY
- — · — INFERRED GEOLOGICAL UNIT BOUNDARY
- BOREHOLE TRACE
- ▼ MEASURED GROUNDWATER DIP 28/08/2023 - 29/08/2023
- ■ RANGE IN TELEMETERED GROUNDWATER DATA 19/10/2023 - 22/03/2024
- ■ PIEZOMETER SCREEN DEPTH

NOTES

VERTICAL AND HORIZONTAL SCALE - 1:1
DEPTH OF LESS CEMENTED AWHITU SAND FORMATION INFERRED FROM BOREHOLE DATA AND APPROXIMATED TO TOPOGRAPHICAL SURFACE
LIMITED INVESTIGATION DATA AVAILABLE, AS SUCH GROUNDWATER SURFACE HAS NOT BEEN INTERPOLATED BETWEEN BOREHOLES



Rev	Description	Date
01	FOR ILLUSTRATION	30/04/2024

GHD

Level 3, GHD Centre
27 Napier Street, Freemans Bay
Auckland 1011 New Zealand
T 64 9 370 8000 **F** 64 9 370 8001
E aklmail@ghd.com **W** www.ghd.com

www.ghd.com

GHD Limited

Project No. 12612462

Client AUCKLAND COUNCIL

Project WAITAKERE COASTAL COMMUNITIES
LANDSLIDE RISK ASSESSMENT - MURIWAI

Status FINAL

Status Code S4

Drawing Title MURIWAI CROSS SECTIONS
CROSS SECTION D-D' (S17)

Size A1

Drawing No. APPENDIX A123

Rev 01

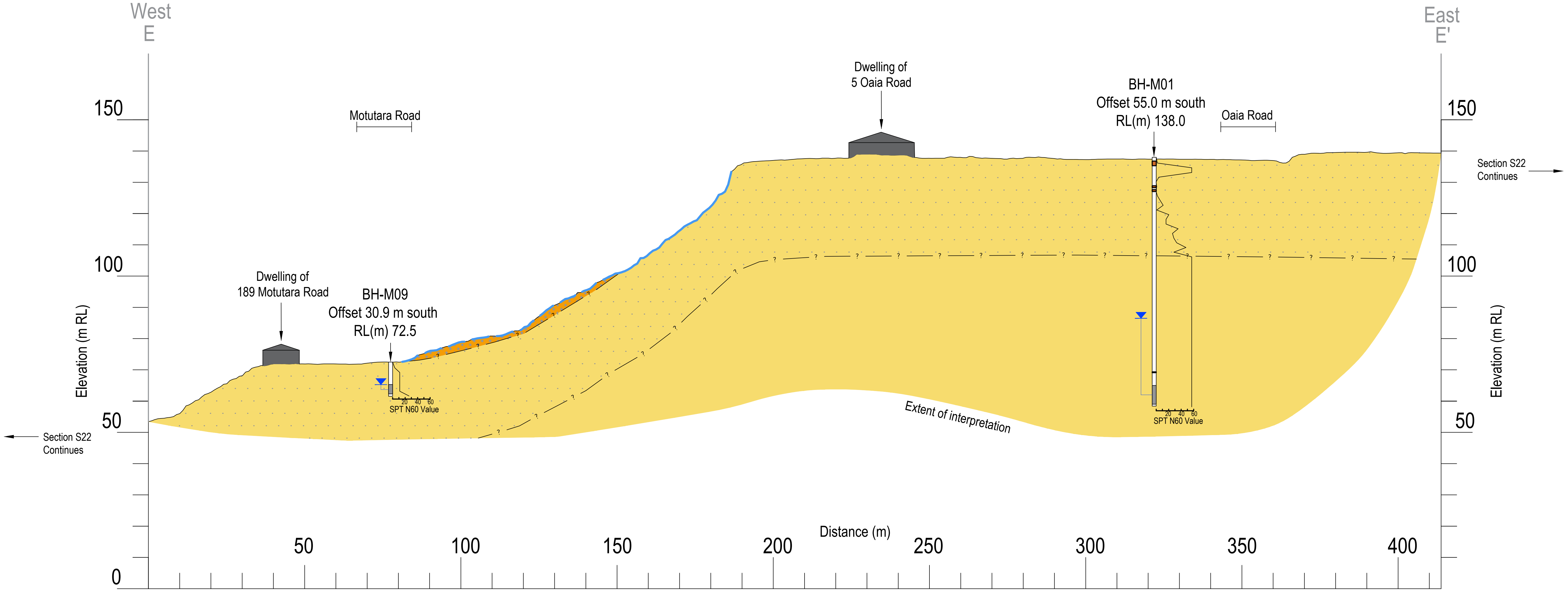
Plot Date: 24 April 2024 - 4:45 pm Plotted by: Luke Agnew File Name: N:\NZ\Auckland\Projects\51\12612462\04 GHD Working\22 Muriwai Cross Sections\02 Section lines\Section 17\12612462_GEOT_DRAWING - Section 17_3.dwg

LEGEND

- ▨ FILL
- 🟧 RECENT COLLUVIUM - POST-2023 LANDSLIDE EVENTS
- 🟨 INFERRED ANCIENT HISTORICAL COLLUVIAL/ALLUVIAL DEPOSITS
- ▨ MITIWAI SAND FORMATION: AEOLIAN DUNE SANDS
- 🟫 AWHITU SAND FORMATION: SILT/CLAY*
- ⬛ AWHITU SAND FORMATION: ORGANIC SOIL/PEAT*
- ▨ AWHITU SAND FORMATION: LESS CEMENTED SAND SPT = <50
- 🟨 AWHITU SAND FORMATION: MORE CEMENTED SAND SPT = 50+
- 🟥 NIHOTUPU FORMATION: SILT/CLAY
- — · — INFERRED GEOLOGICAL UNIT BOUNDARY
- —— APPROXIMATE EXTENT OF LANDSLIDE M-LS02 DEPLETION ZONE
- — — APPROXIMATE EXTENT OF LANDSLIDE M-LS02 ACCUMULATION ZONE
- BOREHOLE TRACE
- ▼ MEASURED GROUNDWATER DIP 17/04/2024
- PIEZOMETER SCREEN DEPTH

NOTES

VERTICAL AND HORIZONTAL SCALE - 1:1
DEPTH OF LESS CEMENTED AWHITU SAND FORMATION INFERRED FROM BOREHOLE DATA AND APPROXIMATED TO TOPOGRAPHICAL SURFACE
REFER TO APPENDIX B, SECTION B4.3.1 'DATA LIMITATIONS' REGARDING POSSIBLE ERROR IN CONTINUOUS READINGS FROM PIEZOMETERS BH-M01 AND BH-M09. THUS, SINGLE READING VALUES HAVE BEEN ILLUSTRATED BELOW



01 FOR ILLUSTRATION	30/04/24
Rev Description	**Date**

GHD Limited
Level 3, GHD Centre
27 Napier Street, Freemans Bay
Auckland 1011 New Zealand
T 64 9 370 8000 **F** 64 9 370 8001
E aklmail@ghd.com **W** www.ghd.com

www.ghd.com

Project No. 12612462

Client AUCKLAND COUNCIL

Project WAITAKERE COASTAL COMMUNITIES
LANDSLIDE RISK ASSESSMENT - MURIWAI

Status FINAL
Status Code S4

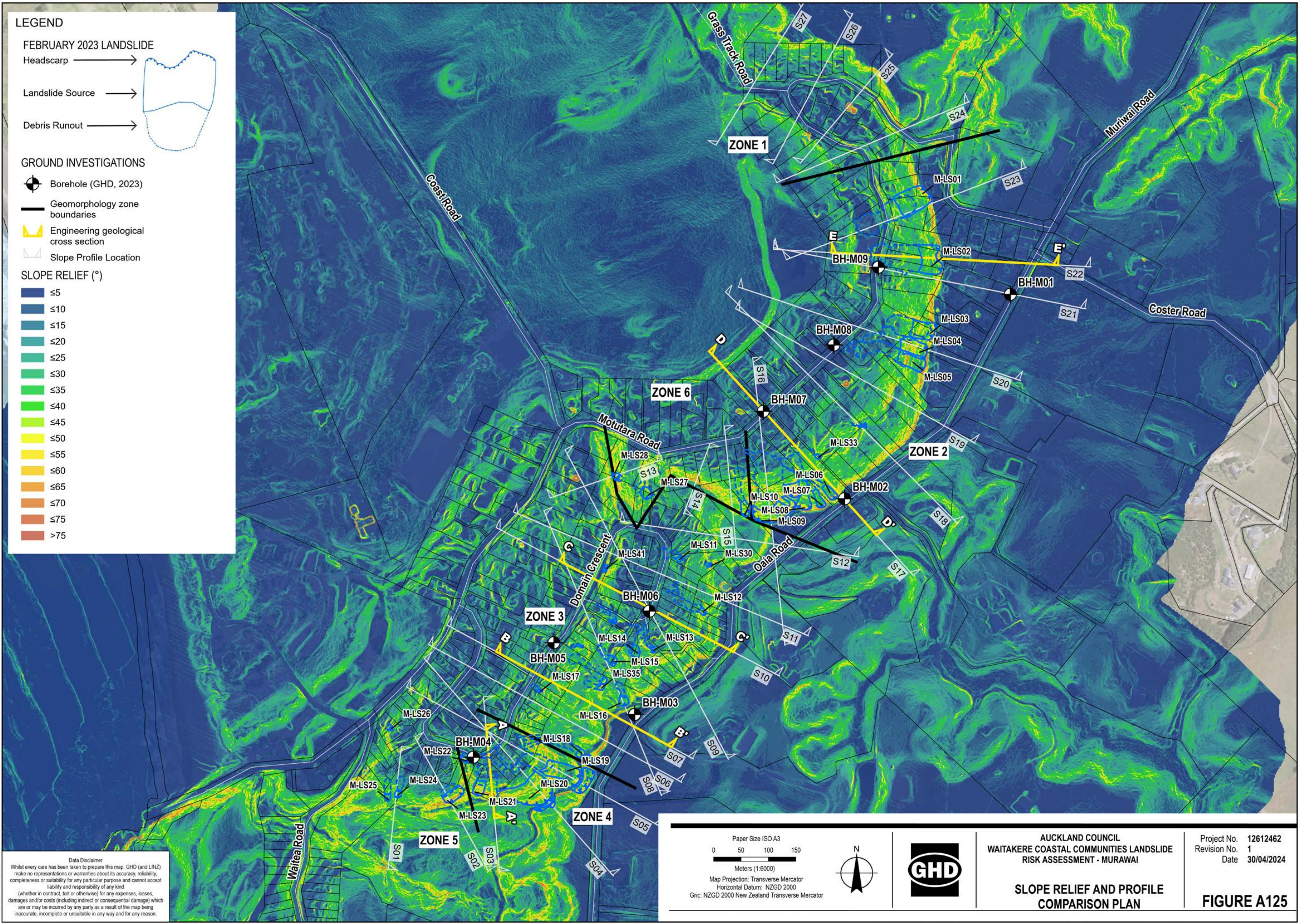
Drawing Title MURIWAI CROSS SECTIONS
CROSS SECTION E-E' (S22)

Size A1

Drawing No. APPENDIX A124

Rev 01

Plot Date: 29 April 2024 - 1:59 pm Plotted by: Luke Agnew File Name: N:\NZ\Auckland\Projects\51\12612462\04 GHD Working\22 Muriwai Cross Sections\02 Section lines\Section 22\12612462r_GEOT_DRAWING - Section 22.dwg



Map Projection: Transverse Mercator
Horizontal Datum: NZGD 2000
Grid: NZGD 2000 New Zealand Transverse Mercator

AUCKLAND COUNCIL
WAITAKERE COASTAL COMMUNITIES LANDSLIDE RISK ASSESSMENT - MURAWAI

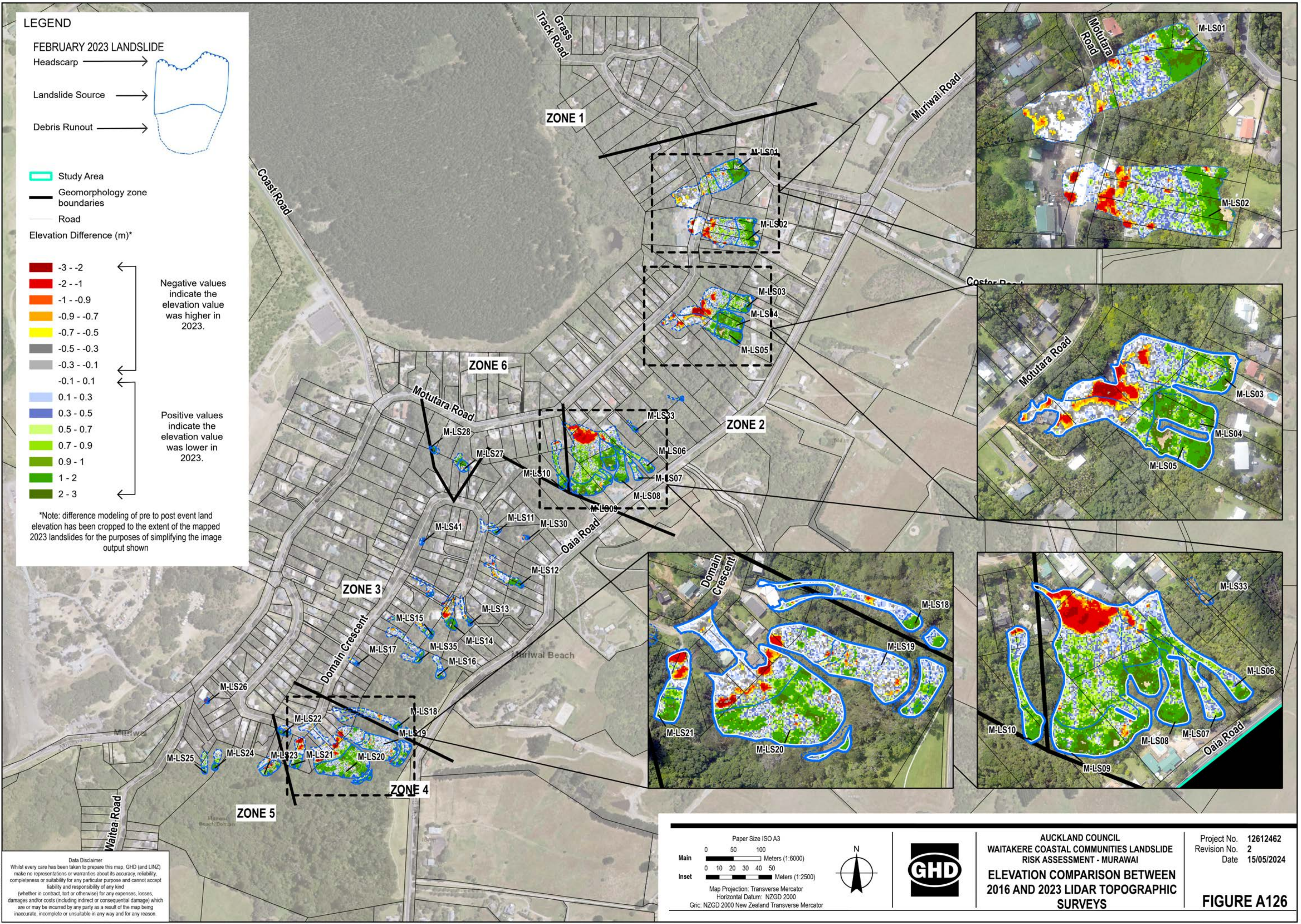
SLOPE RELIEF AND PROFILE COMPARISON PLAN

Project No.	12612462
Revision No.	1
Date	30/04/2024

FIGURE A125

Data source: World Topographic Map: LINZ, Stats NZ, Esri, HERE, Garmin, USGS
World Topographic Map: Stats NZ, Esri, TomTom, Garmin, Foursquare, METI/NASA, USGS
World Hillshade: Esri, NASA, NGA, USGS
NZ - Imagery: Eagle Technology, LINZ; GHD - Site boundary, Placard status, Cross Sections - 20230626. AC-DTM -20230626, LINZ - Parce, road - 20230626 Created by: nrama

\\ghdnet\ghd\NZ\Auckland\Projects\51\12612462\GIS\Maps\Working\12612462_Geotech_Murawai_AppA.aprx
Print date: 24 Apr 2024 - 18:46



Paper Size ISO A3

Main 0 50 100 Meters (1:6000)

Inset 0 10 20 30 40 50 Meters (1:2500)

Map Projection: Transverse Mercator
Horizontal Datum: NZGD 2000
Grid: NZGD 2000 New Zealand Transverse Mercator

N

AUCKLAND COUNCIL
WAITAKERE COASTAL COMMUNITIES LANDSLIDE RISK ASSESSMENT - MURAWAI

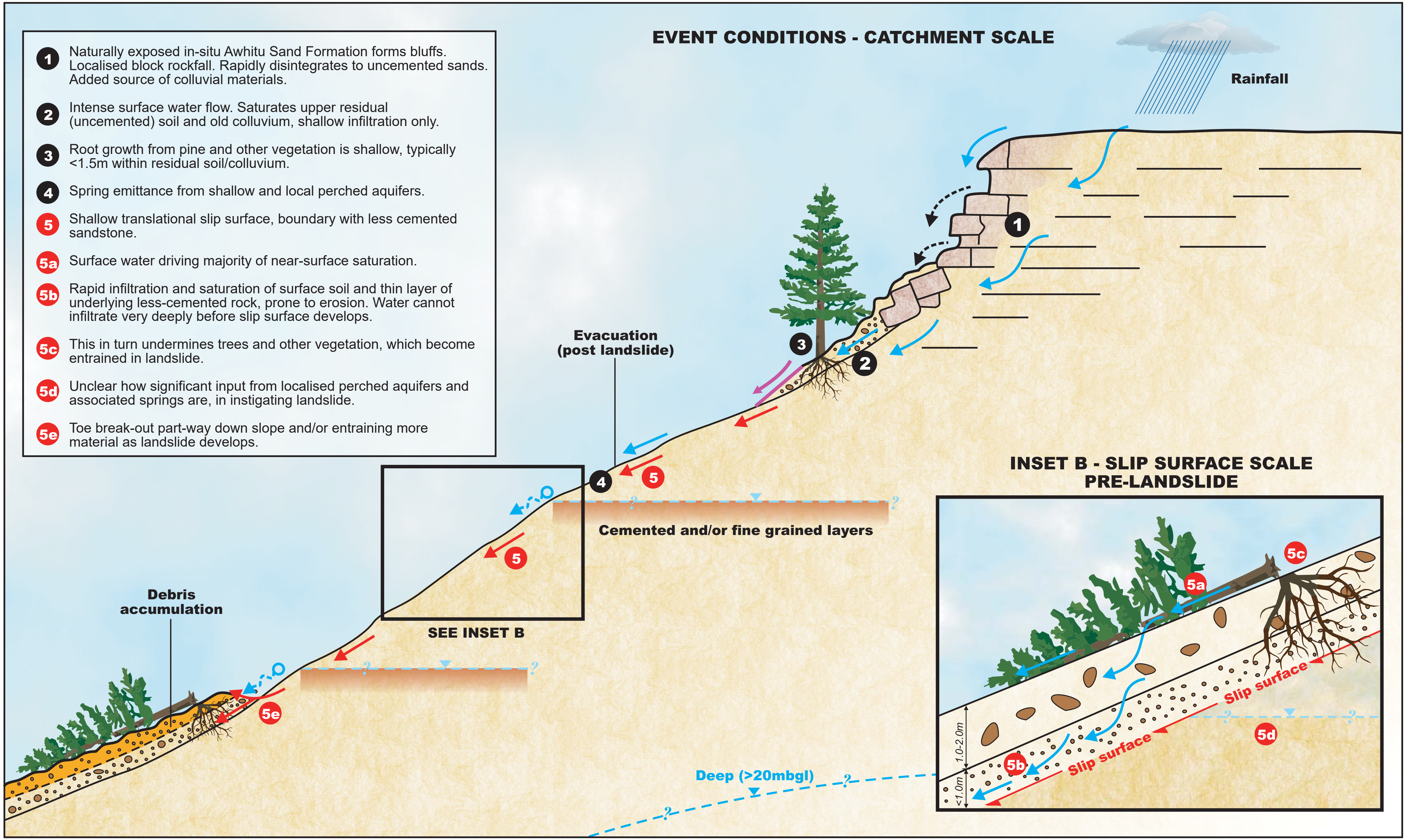
ELEVATION COMPARISON BETWEEN 2016 AND 2023 LIDAR TOPOGRAPHIC SURVEYS

Project No.	12612462
Revision No.	2
Date	15/05/2024

FIGURE A126

\\ghdnet\ghd\NZ\Auckland\Projects\51\12612462\GIS\Maps\Working\12612462_Geotech_Murawai_AppA.aprx
Print date: 15 May 2024 - 12:24

Data source: World Topographic Map: LINZ, Stats NZ, Esri, HERE, Garmin, USGS
World Topographic Map: Stats NZ, Esri, TomTom, Garmin, Foursquare, METI/NASA, USGS
World Hillshade: Esri, NASA, NGA, USGS
NZ - Imagery: Eagle Technology, LINZ; GHD - Site boundary, Placard status, Cross Sections - 20230626. AC-DTM -20230626, LINZ - Parce, road - 20230626 Created by: nrama



1 Naturally exposed in-situ Awhitu Sand Formation forms bluffs. Localised block rockfall. Rapidly disintegrates to uncemented sands. Added source of colluvial materials.

2 Intense surface water flow. Saturates upper residual (uncemented) soil and old colluvium, shallow infiltration only.

3 Root growth from pine and other vegetation is shallow, typically <1.5m within residual soil/colluvium.

4 Spring emittance from shallow and local perched aquifers.

5 Shallow translational slip surface, boundary with less cemented sandstone.

5a Surface water driving majority of near-surface saturation.

5b Rapid infiltration and saturation of surface soil and thin layer of underlying less-cemented rock, prone to erosion. Water cannot infiltrate very deeply before slip surface develops.

5c This in turn undermines trees and other vegetation, which become entrained in landslide.

5d Unclear how significant input from localised perched aquifers and associated springs are, in instigating landslide.

5e Toe break-out part-way down slope and/or entraining more material as landslide develops.

LEGEND

- ▨ Residual soil and old colluvium
- ▭ Less cemented Awhitu Group Sands (N = <50+)
- ☰ Strata
- ← Slip surface
- ←-- Isolated rock fall
- –▼– Regional groundwater profile
- –▼– Perched aquifer
- ← Water flow
- ←∙∙○ Surface spring
- // Headscarp

Conceptual diagram only - not to scale

AUCKLAND COUNCIL
WAITAKERE COASTAL COMMUNITIES LANDSLIDE RISK ASSESSMENT

Project No. 12612462
Revision No. 01
Date 30/04/2024

2023 CYCLONE GABRIELLE LANDSLIDE MECHANISM MODEL, MURIWAI

FIGURE A127

AU\Launceston\Projects\Admin\Graphics\12\612462\12612462_LST00_08.cdr

Level 2, 29 Christie Street St Leonards NSW 2065 T 61 2 9462 4700 F 61 2 9462 4710 E slnmail@ghd.com W www.ghd.com

Rev	Description	Checked	Approved	Date
00	FOR ILLUSTRATION	LA	NB	30/04/23

GHD
138 Victoria Street, Level 3,
Christchurch Central, Canterbury 8013, New Zealand
T +64 33780900 F +64 33778575
E chcmail@ghd.com W www.ghd.com
www.ghd.com

GHD Limited

Project No.

Client AUCKLAND COUNCIL

Project WAITAKERE COSTAL COMMUNITIES LANDSLIDE RISK ASSESSMENT - MURIWAI

Status FOR ILLUSTRATION

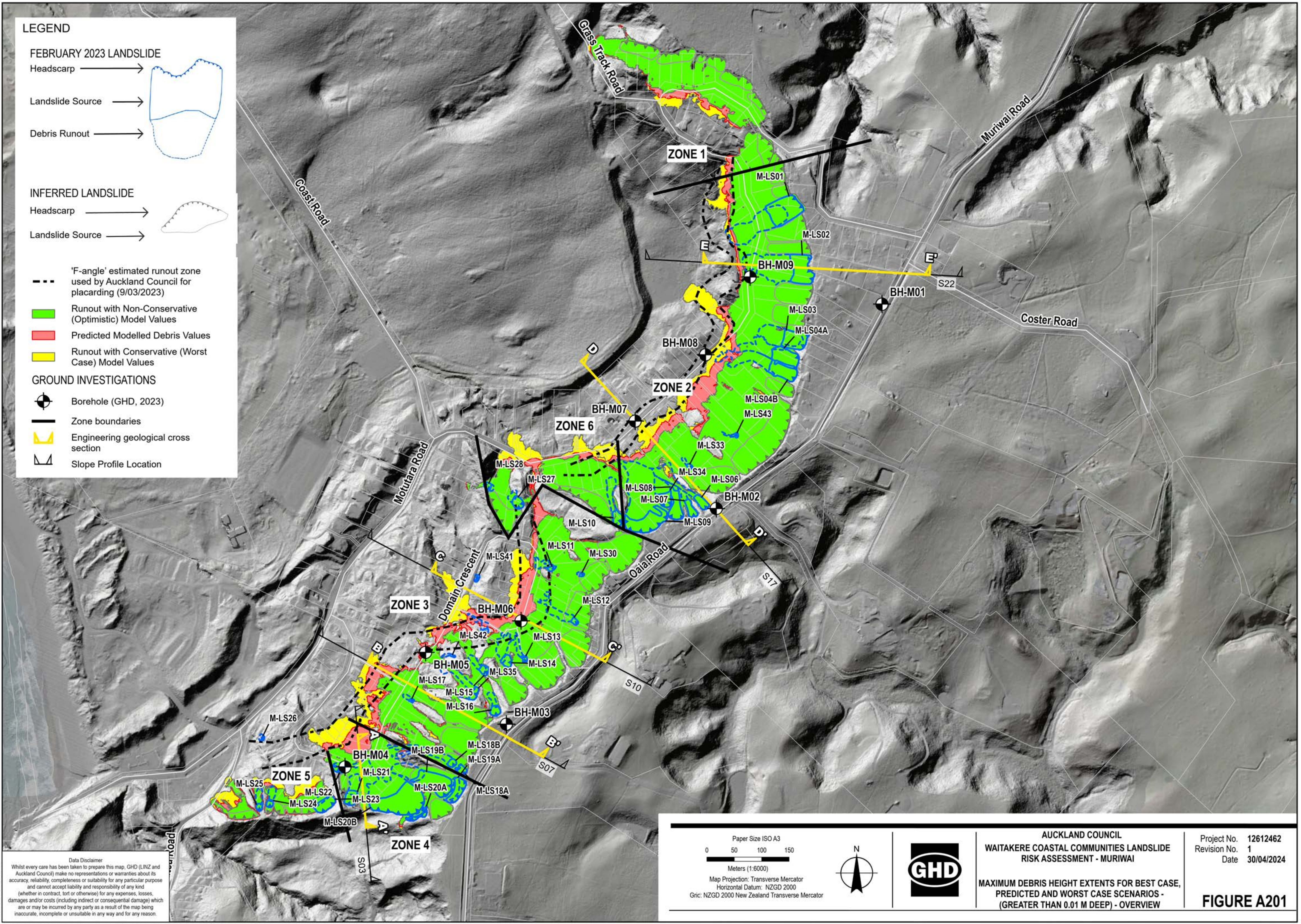
Status Code S4

Drawing Title 2023 CYCLONE GABRIELLE LANDSLIDE MECHANISM MODEL, MURIWAI - PHOTO MARK-UP

Size A1

Drawing No APPENDIX A128

Rev 0



Paper Size ISO A3

0 50 100 150

Meters (1:6000)

Map Projection: Transverse Mercator
Horizontal Datum: NZGD 2000
Gric: NZGD 2000 New Zealand Transverse Mercator

GHD

AUCKLAND COUNCIL
WAITAKERE COASTAL COMMUNITIES LANDSLIDE
RISK ASSESSMENT - MURIWAI

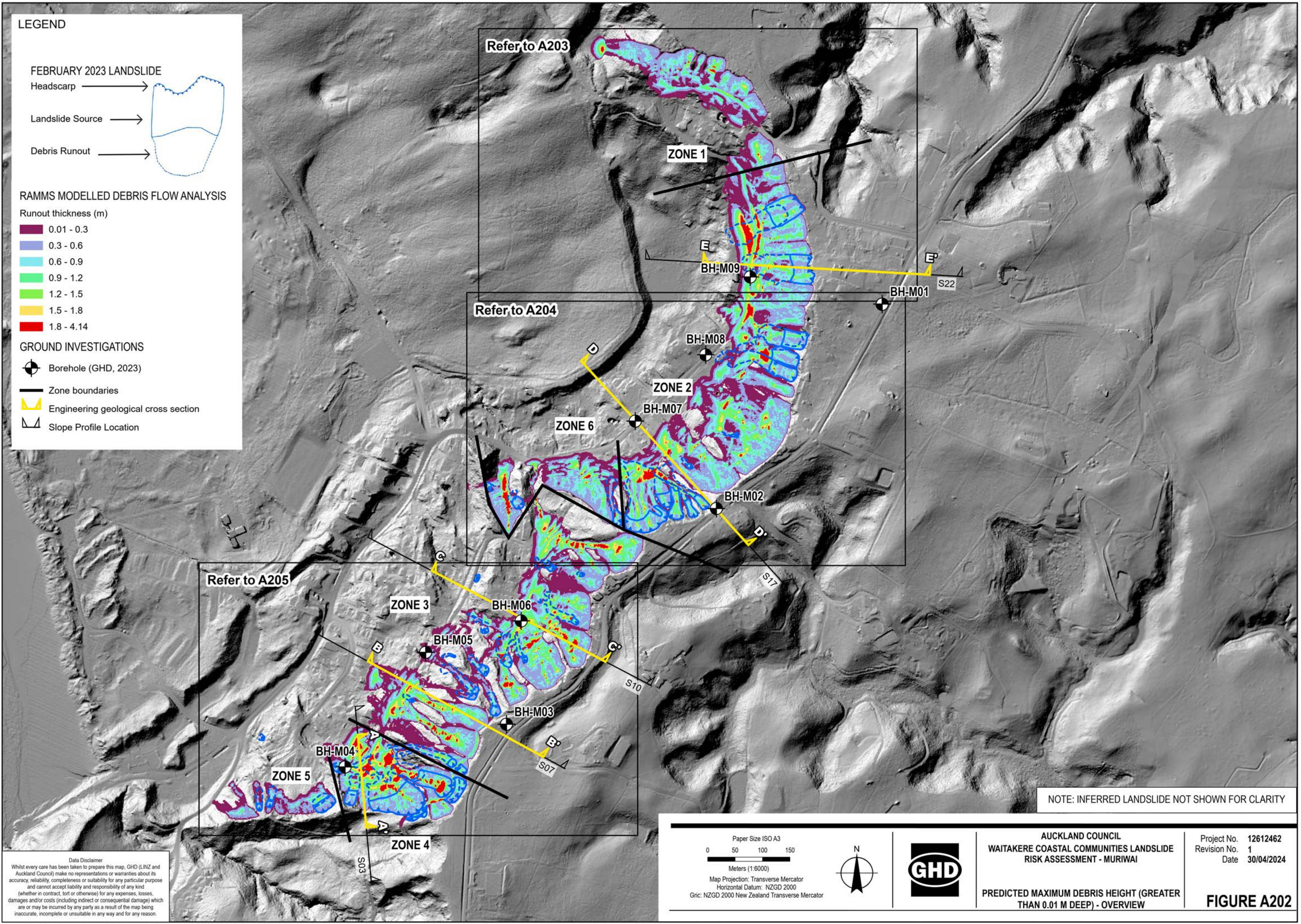
MAXIMUM DEBRIS HEIGHT EXTENTS FOR BEST CASE,
PREDICTED AND WORST CASE SCENARIOS -
(GREATER THAN 0.01 M DEEP) - OVERVIEW

Project No.	12612462
Revision No.	1
Date	30/04/2024

FIGURE A201

\\ghdnet\ghd\NZ\Auckland\Projects\51\12612462\GIS\Maps\Working\12612462_Geotech_Muriwai_AppA.aprx
Print date: 29 Apr 2024 - 08:45

Data source: World Imagery: Auckland Council, Maxar; LINZ- Parcel, Road. Auckland Council - F- angle, GHD - Inferred landslides, February Landslides, RAMMS Landslide Prediction - 20230724. Created by: nrama



NOTE: INFERRED LANDSLIDE NOT SHOWN FOR CLARITY

Paper Size ISO A3

0 50 100 150

Meters (1:6000)

Map Projection: Transverse Mercator
Horizontal Datum: NZGD 2000
Gric: NZGD 2000 New Zealand Transverse Mercator

AUCKLAND COUNCIL
WAITAKERE COASTAL COMMUNITIES LANDSLIDE RISK ASSESSMENT - MURIWAI

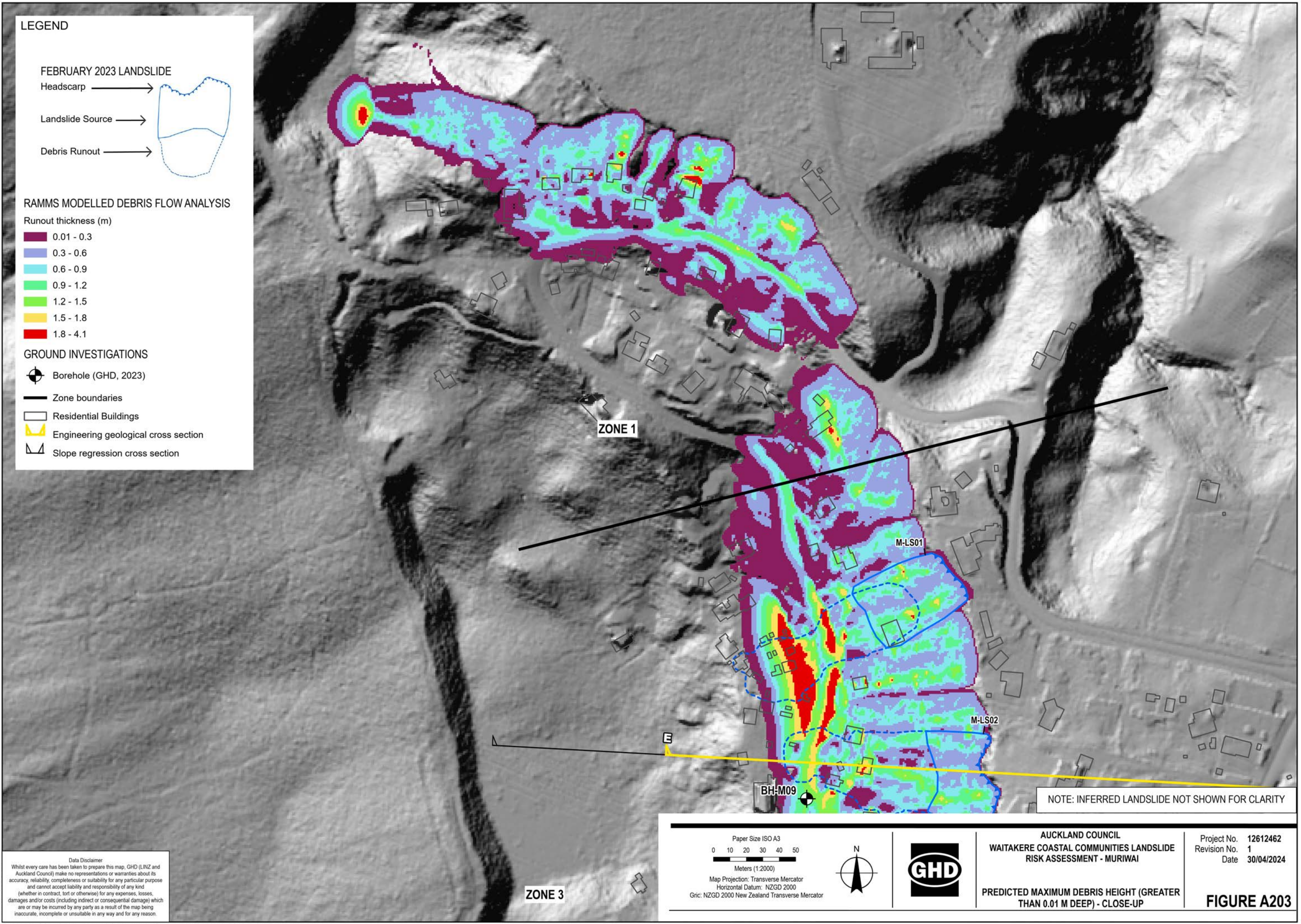
PREDICTED MAXIMUM DEBRIS HEIGHT (GREATER THAN 0.01 M DEEP) - OVERVIEW

Project No.	12612462
Revision No.	1
Date	30/04/2024

FIGURE A202

\\ghdnet\ghd\NZ\Auckland\Projects\51\12612462\GIS\Maps\Working\12612462_Geotech_Muriwai_AppA.aprx
Print date: 26 Apr 2024 - 11:37

Data source: ; LINZ- Parcel, Road, Housing number. GHD - Inferred landslides, February Landslides, RAMMS Landslide Prediction - 20230724. Created by: nrama



NOTE: INFERRED LANDSLIDE NOT SHOWN FOR CLARITY

Map Projection: Transverse Mercator
Horizontal Datum: NZGD 2000
Grid: NZGD 2000 New Zealand Transverse Mercator

AUCKLAND COUNCIL
WAITAKERE COASTAL COMMUNITIES LANDSLIDE
RISK ASSESSMENT - MURIWAI

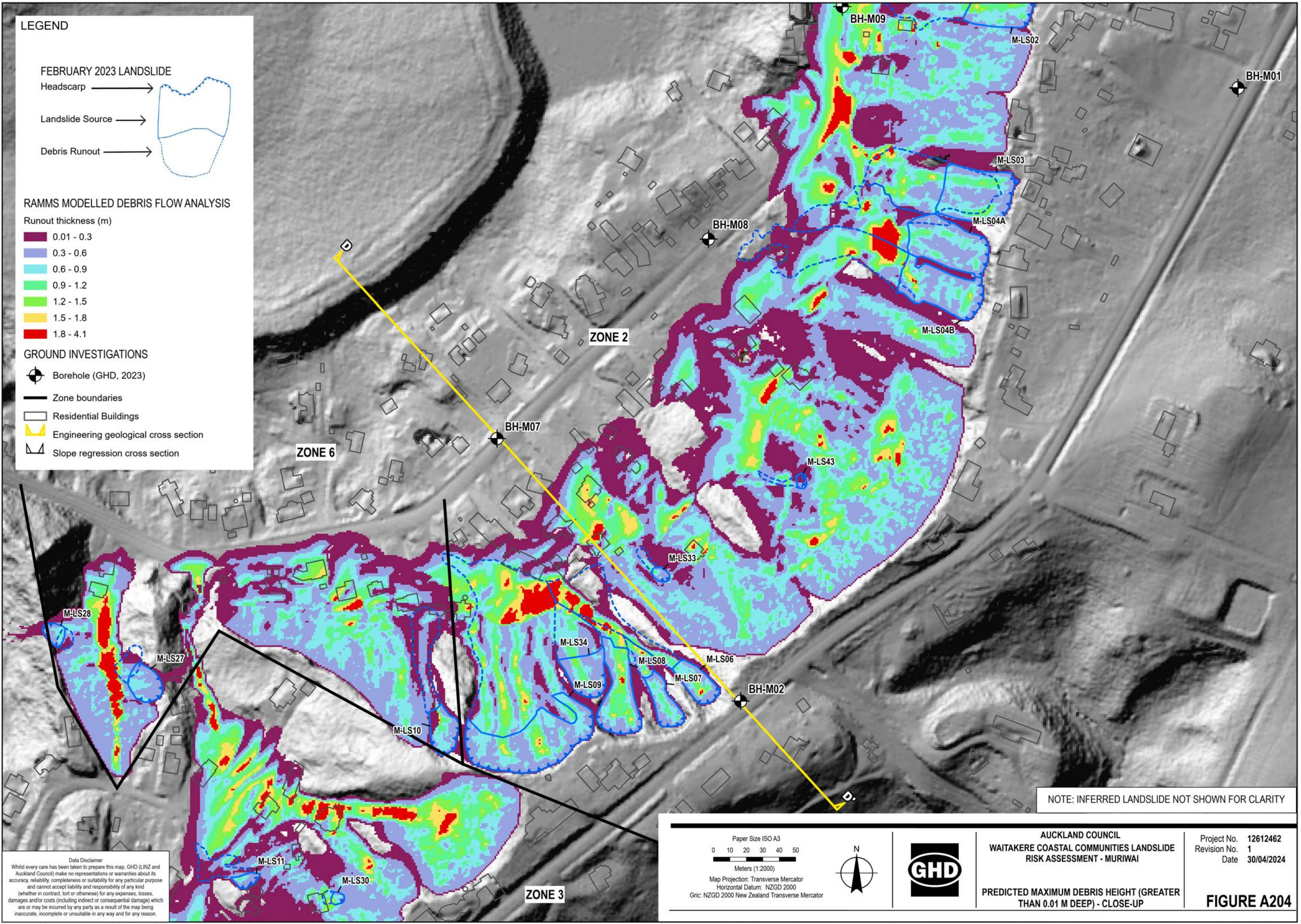
PREDICTED MAXIMUM DEBRIS HEIGHT (GREATER THAN 0.01 M DEEP) - CLOSE-UP

Project No. 12612462
Revision No. 1
Date 30/04/2024

FIGURE A203

Data source: ; LINZ- Parcel, Road, Housing number. GHD - Inferred landslides, February Landslides, RAMMS Landslide Prediction - 20230724. Created by: nrama

\\ghdnet\ghd\NZ\Auckland\Projects\51\12612462\GIS\Maps\Working\12612462_Geotech_Murawai_AppA.aprx
Print date: 26 Apr 2024 - 11:46



NOTE: INFERRED LANDSLIDE NOT SHOWN FOR CLARITY

Paper Size ISO A3

0 10 20 30 40 50

Meters (1:2000)

Map Projection: Transverse Mercator
Horizontal Datum: NZGD 2000
Grid: NZGD 2000 New Zealand Transverse Mercator

GHD

AUCKLAND COUNCIL
WAITAKERE COASTAL COMMUNITIES LANDSLIDE RISK ASSESSMENT - MURIWAI

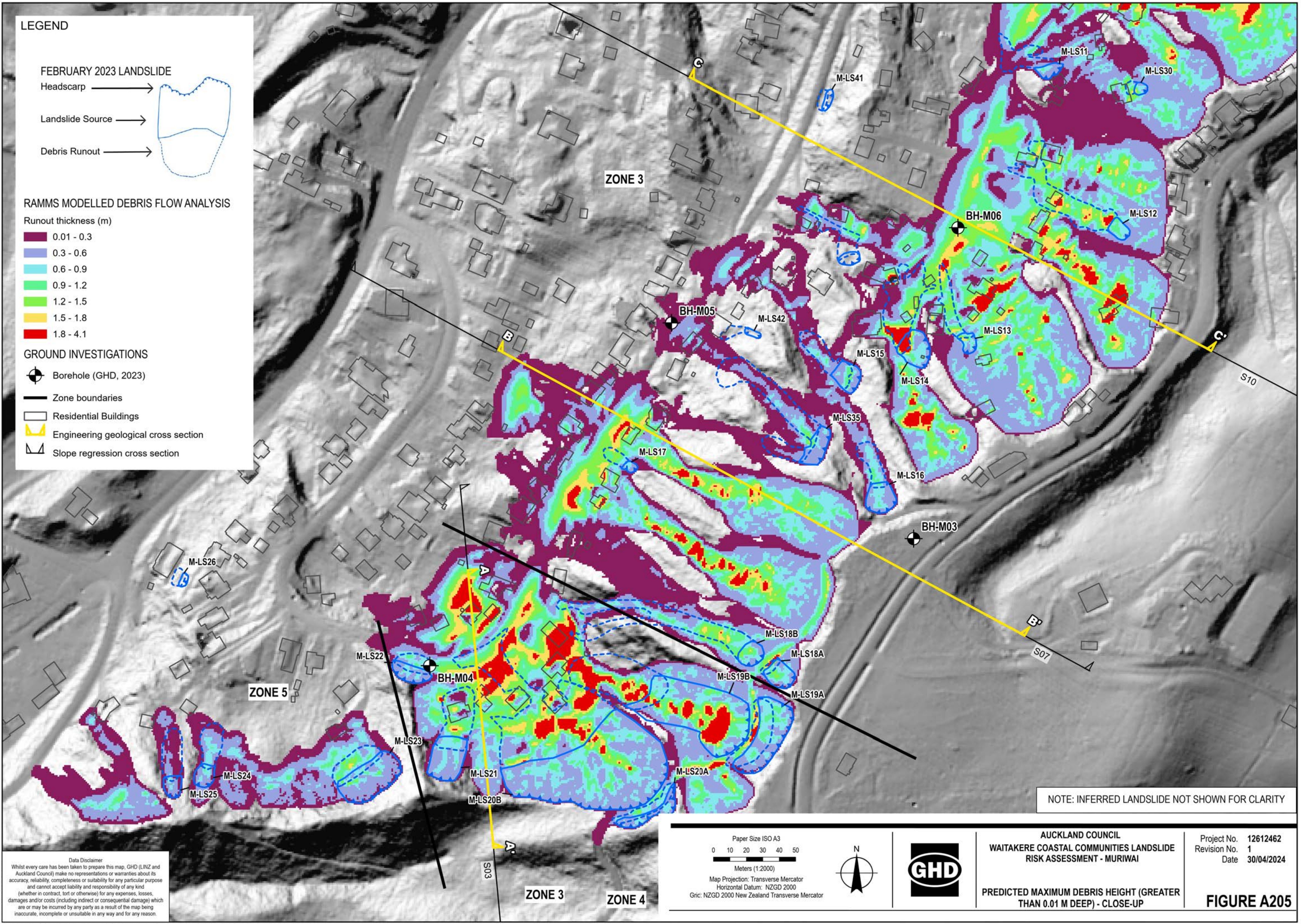
PREDICTED MAXIMUM DEBRIS HEIGHT (GREATER THAN 0.01 M DEEP) - CLOSE-UP

Project No. **12612462**
Revision No. **1**
Date **30/04/2024**

FIGURE A204

\\ghdnet\ghd\NZ\Auckland\Projects\51\12612462\GIS\Maps\Working\12612462_Geotech_Murawai_AppA.aprx
Print date: 26 Apr 2024 - 11:46

Data source: ; LINZ- Parcel, Road, Housing number. GHD - Inferred landslides, February Landslides, RAMMS Landslide Prediction - 20230724. Created by: nrama



NOTE: INFERRED LANDSLIDE NOT SHOWN FOR CLARITY

Map Projection: Transverse Mercator
Horizontal Datum: NZGD 2000
Grid: NZGD 2000 New Zealand Transverse Mercator

AUCKLAND COUNCIL
WAITAKERE COASTAL COMMUNITIES LANDSLIDE
RISK ASSESSMENT - MURIWAI

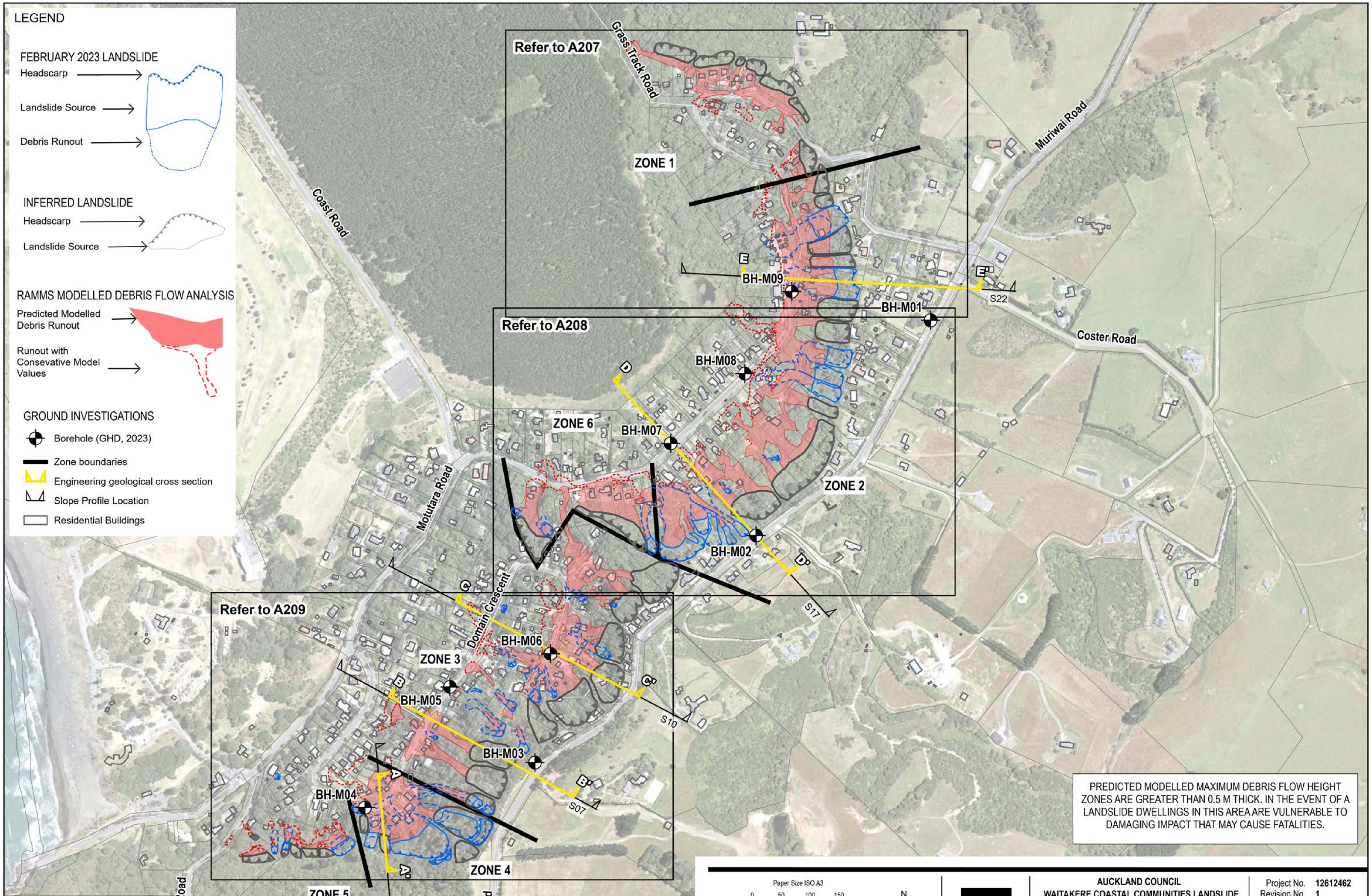
PREDICTED MAXIMUM DEBRIS HEIGHT (GREATER THAN 0.01 M DEEP) - CLOSE-UP

Project No. 12612462
Revision No. 1
Date 30/04/2024

FIGURE A205

Data source: ; LINZ- Parcel, Road, Housing number. GHD - Inferred landslides, February Landslides, RAMMS Landslide Prediction - 20230724. Created by: nrama

\\ghdnet\ghd\NZ\Auckland\Projects\51\12612462\GIS\Maps\Working\12612462_Geotech_Murawai_AppA.aprx
Print date: 26 Apr 2024 - 11:47



PREDICTED MODELLED MAXIMUM DEBRIS FLOW HEIGHT ZONES ARE GREATER THAN 0.5 M THICK. IN THE EVENT OF A LANDSLIDE DWELLINGS IN THIS AREA ARE VULNERABLE TO DAMAGING IMPACT THAT MAY CAUSE FATALITIES.

Map Projection: Transverse Mercator
Horizontal Datum: NZGD 2000
Grid: NZGD 2000 New Zealand Transverse Mercator

GHD

AUCKLAND COUNCIL
WAITAKERE COASTAL COMMUNITIES LANDSLIDE RISK ASSESSMENT - MURIWAI

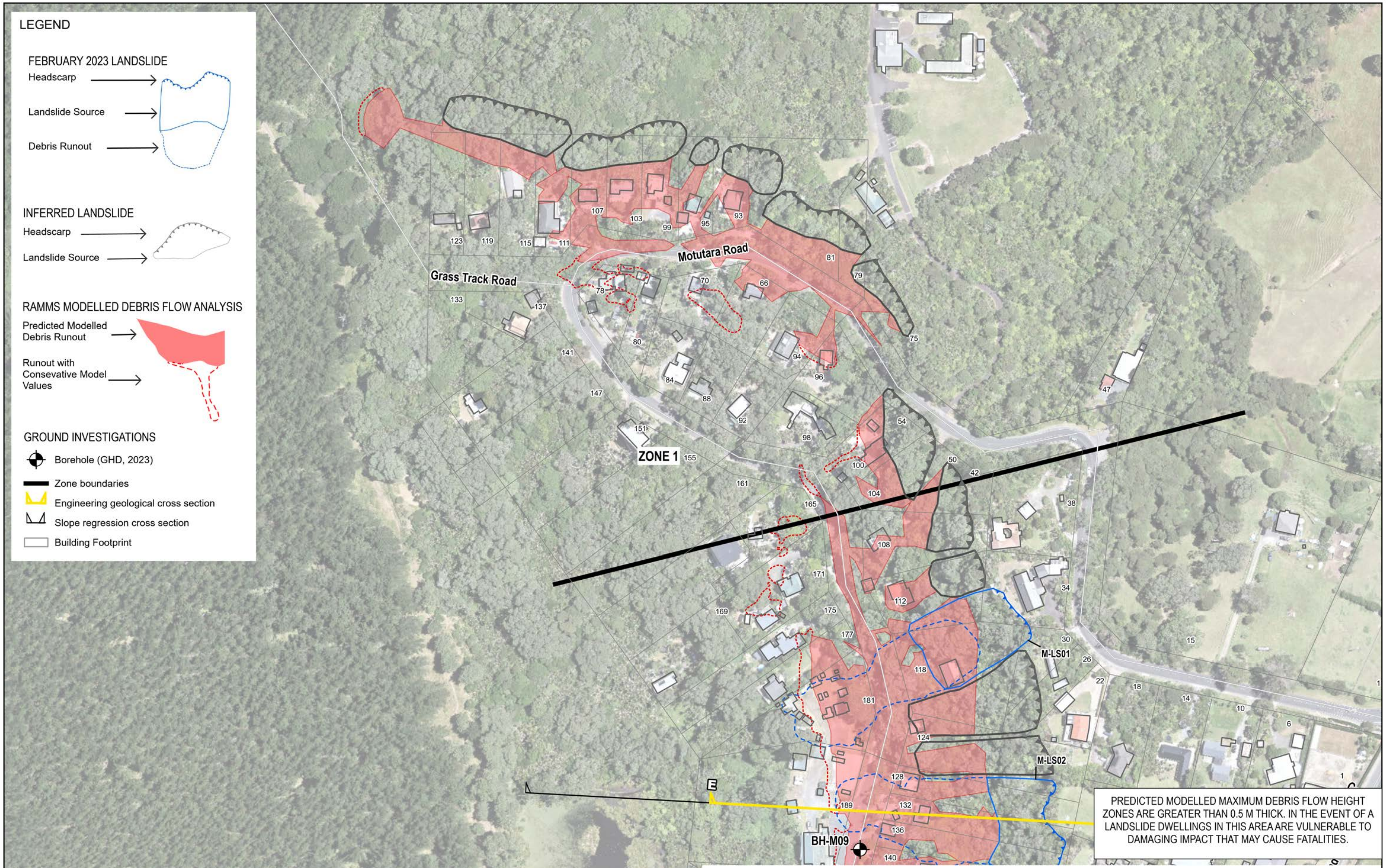
MAXIMUM DEBRIS HEIGHT EXTENTS (GREATER THAN 0.5 M DEEP) - OVERVIEW

Project No. **12612462**
Revision No. **1**
Date **30/04/2024**

FIGURE A206

\\ghdnet\ghd\NZ\Auckland\Projects\51\12612462\GIS\Maps\Working\12612462_Geotech_Muriwai_AppA.aprx
Print date: 26 Apr 2024 - 11:39

Data source: World Imagery: Auckland Council, Maxar; GHD - Inferred landslides, February Landslides, RAMMS Landslide Prediction - 20230724. Auckland Council - Dwelling Placard (by GHD), Building fooTprint, parcel. Created by: nrama



PREDICTED MODELLED MAXIMUM DEBRIS FLOW HEIGHT ZONES ARE GREATER THAN 0.5 M THICK. IN THE EVENT OF A LANDSLIDE DWELLINGS IN THIS AREA ARE VULNERABLE TO DAMAGING IMPACT THAT MAY CAUSE FATALITIES.

Paper Size ISO A3

0 10 20 30 40 50

Meters (1:2000)

Map Projection: Transverse Mercator
Horizontal Datum: NZGD 2000
Gric: NZGD 2000 New Zealand Transverse Mercator

N

GHD

AUCKLAND COUNCIL
WAITAKERE COASTAL COMMUNITIES LANDSLIDE RISK ASSESSMENT - MURIWAI

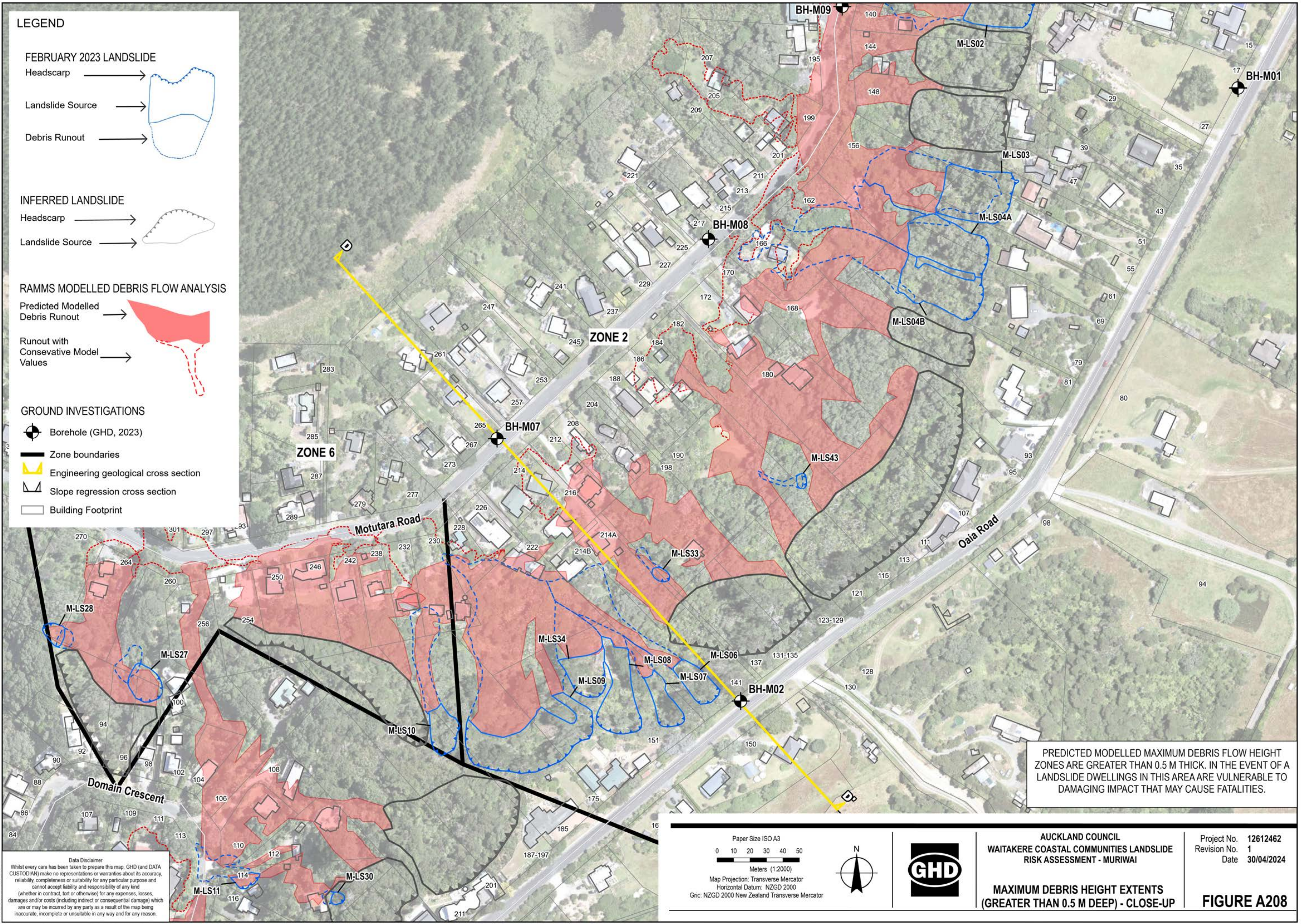
MAXIMUM DEBRIS HEIGHT EXTENTS (GREATER THAN 0.5 M DEEP) - CLOSE-UP

Project No.	12612462
Revision No.	1
Date	30/04/2024

FIGURE A207

\\ghdnet\ghd\NZ\Auckland\Projects\51\12612462\GIS\Maps\Working\12612462_Geotech_Muriwai_AppA.aprx
Print date: 26 Apr 2024 - 12:43

Data source: World Topographic Map: Stats NZ, Esri, TomTom, Garmin, Foursquare, METI/NASA, USGS
World Imagery: Auckland Council, LINZ
World Hillshade: Esri, NASA, NGA, USGS; GHD - Inferred landslides, February Landslides, RAMMS Landslide Prediction - 20230724. Auckland Council - Dwelling Placard (by GHD), Building footprint, parcel. Created by: nrama



LEGEND

FEBRUARY 2023 LANDSLIDE
Headscarp
Landslide Source
Debris Runout

INFERRED LANDSLIDE
Headscarp
Landslide Source

RAMMS MODELLED DEBRIS FLOW ANALYSIS
Predicted Modelled Debris Runout
Runout with Consevative Model Values

GROUND INVESTIGATIONS
Borehole (GHD, 2023)
Zone boundaries
Engineering geological cross section
Slope regression cross section
Building Footprint

PREDICTED MODELLED MAXIMUM DEBRIS FLOW HEIGHT ZONES ARE GREATER THAN 0.5 M THICK. IN THE EVENT OF A LANDSLIDE DWELLINGS IN THIS AREA ARE VULNERABLE TO DAMAGING IMPACT THAT MAY CAUSE FATALITIES.

Paper Size ISO A3
0 10 20 30 40 50
Meters (1:2000)
Map Projection: Transverse Mercator
Horizontal Datum: NZGD 2000
Grid: NZGD 2000 New Zealand Transverse Mercator

N

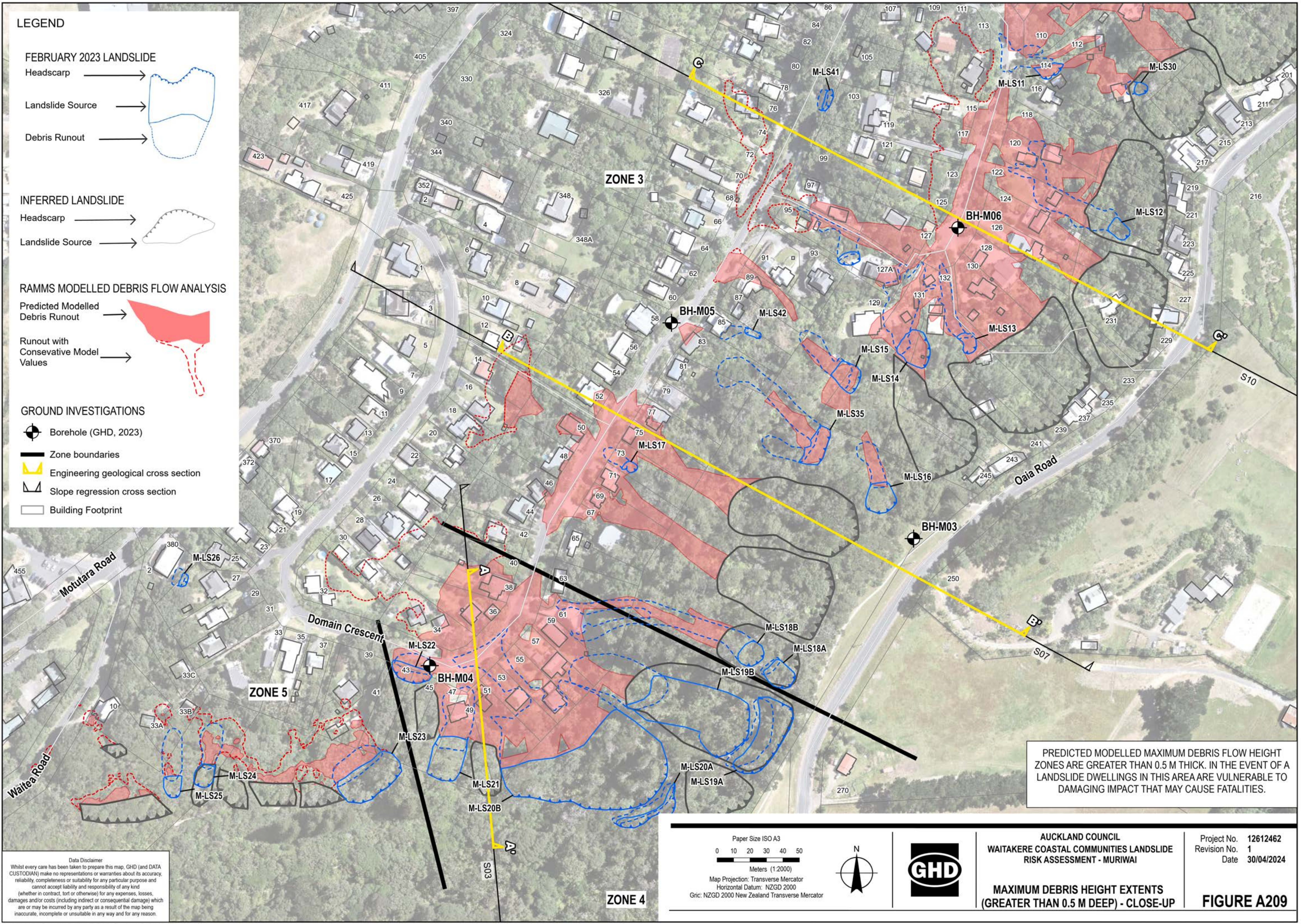
AUCKLAND COUNCIL
WAITAKERE COASTAL COMMUNITIES LANDSLIDE RISK ASSESSMENT - MURIWAI

MAXIMUM DEBRIS HEIGHT EXTENTS (GREATER THAN 0.5 M DEEP) - CLOSE-UP

Project No. 12612462
Revision No. 1
Date 30/04/2024

FIGURE A208

Data source: World Topographic Map: Stats NZ, Esri, TomTom, Garmin, Foursquare, METI/NASA, USGS
World Imagery: Auckland Council, Maxar
World Hillshade: Esri, NASA, NGA, USGS; GHD - Inferred landslides, February Landslides, RAMMS Landslide Prediction - 20230724. Auckland Council - Dwelling Placard (by GHD), Building footprint, parcel. Created by: nrama



PREDICTED MODELLED MAXIMUM DEBRIS FLOW HEIGHT ZONES ARE GREATER THAN 0.5 M THICK. IN THE EVENT OF A LANDSLIDE DWELLINGS IN THIS AREA ARE VULNERABLE TO DAMAGING IMPACT THAT MAY CAUSE FATALITIES.

Paper Size ISO A3
0 10 20 30 40 50
Meters (1:2000)
Map Projection: Transverse Mercator
Horizontal Datum: NZGD 2000
Gric: NZGD 2000 New Zealand Transverse Mercator

AUCKLAND COUNCIL
WAITAKERE COASTAL COMMUNITIES LANDSLIDE RISK ASSESSMENT - MURIWAI

MAXIMUM DEBRIS HEIGHT EXTENTS (GREATER THAN 0.5 M DEEP) - CLOSE-UP

Project No. **12612462**
Revision No. **1**
Date **30/04/2024**

FIGURE A209

Data source: World Topographic Map: Stats NZ, Esri, TomTom, Garmin, Foursquare, METI/NASA, USGS
World Imagery: Auckland Council, LINZ
World Hillshade: Esri, NASA, NGA, USGS; GHD - Inferred landslides, February Landslides, RAMMS Landslide Prediction - 20230724. Auckland Council - Dwelling Placard (by GHD), Building footprint, parcel. Created by: nrama

\\ghdnet\ghd\NZ\Auckland\Projects\51\12612462\GIS\Maps\Working\12612462_Geotech_Muriwai_AppA.aprx
Print date: 26 Apr 2024 - 12:44

Appendix B

Engineering Geological Report

Waitakere Coastal Communities Landslide Risk Assessment

Appendix B – Muriwai Engineering Geological Report

Auckland Council

15 May 2024

→ The Power of Commitment

Project name	Waitakere Coastal Communities Landslide Risk Assessment
Document title	Waitakere Coastal Communities Landslide Risk Assessment | Appendix B – Muriwai Engineering Geological Report
Project number	12612462
File name	12612462_Appendix B_Rev2.docx

Status Code	**Revision**	**Author**	**Reviewer**		**Approved for issue**		
			Name	**Signature**	**Name**	**Signature**	**Date**
S4	0	Nick Burke	Don Macfarlane	D Macfarlane	Roy Pearson	Roy Pearson	3/11/2023
S4	1	Nick Burke	Don Macfarlane	D Macfarlane	Roy Pearson	Roy Pearson	30/04/2024
S4	2	Nick Burke	Don Macfarlane	D Macfarlane	Roy Pearson	Roy Pearson	15/05/2024
[Status code]							
[Status code]							

GHD Limited
Contact: Matt Howard, Technical Director - Engineering Geologist | GHD
27 Napier Street, GHD Centre Level 3
Freemans Bay, Auckland 1010, New Zealand
T +64 9 370 8000 | **F** +64 9 370 8001 | **E** aklmail@ghd.com | **ghd.com**

→ The Power of Commitment

Contents

Table index

Figure index

Appendices

B1. Introduction

B1.1 Background

Two significant rainfall events affected the Waitakere area in late January and early February, resulting from the impacts of ex-tropical cyclones Hale and Gabrielle, respectively.

The Cyclone Gabrielle weather event of 14 February 2023 resulted in widespread catastrophic flooding and slope instability in the settlement of Muriwai where several debris avalanches (which included rocks and trees) occurred, some of which developed into saturated debris flows that resulted in damage to buildings and infrastructure. Two fatalities occurred due to impact of landslides on private dwellings. This tragic event was similar to a 1965 storm event that also claimed two lives.

Following the event, rapid building assessment of residential properties was undertaken in Muriwai, with some houses having access by owners restricted (a yellow placard – e.g., access in daylight hours only) and some for which no access was permitted (a red placard).

B1.2 Purpose of this report

GHD was engaged by Auckland Council (AC)[1] to carry out landslide risk assessments and to provide associated landslide risk management advice and geotechnical investigations in the Waitakere area, specifically for the residential areas of Muriwai, Piha and Karekare.

The purpose of this report is to present an engineering geological assessment of the Muriwai area to explain the context in which the damaging landslides of February 2023 occurred. This report is informed by remotely acquired topography data, historical information, community observations, geological mapping, subsurface geotechnical investigations and materials testing.

This report is an appendix to the overall GHD landslide risk report and should be read in conjunction with it, as well as the other associated appendices. The overall report contains additional information and synthesises the results of other appended assessments carried out by GHD (refer to Section B1.4).

B1.3 Scope

The agreed scope for this engineering geology assessment was as follows:

- Assemble GIS database information relating to topography, land use, geology and geohazards from publicly available sources, and that provided by AC. This has been used as a basis for presenting our findings.
- Undertake desktop and ground-based engineering geological mapping of the Muriwai settlement, focussing on characterisation of recent landslides and associated geological landforms.
- Present classification and indexing of recent large landslides within the Muriwai settlement.
- Present a summary of anecdotal evidence gathered from local community members that relates to geohazards, such as previous observations of ground instability or surface water flows.
- Review publicly available literature associated with Muriwai geology and landslide hazard.
- Provide an interpretation of the geology and geomorphology of Muriwai to understand possible future landslide distribution, characteristics and triggering mechanism(s).

Geotechnical ground investigations took place at the same time as the work described above and are presented in Appendix F.

---

[1] Under Contract CW198379, Master Services Agreement CCCS: CW74240 dated 7/09/2019

The focus of this study is limited to the assessment of the effects from 'large scale' landslide[2] hazards originating from the main escarpment located to the south-east of Muriwai because this is where damaging, fatality-causing landslides have historically originated. Smaller, more localised landslide hazards (on the scale of less than a property section wide or long) are not considered as they rarely lead to loss-of-life. The combination of numerous, small landslides would be considered if it were to result in a damaging debris flow.

Excluded from this report is consideration of the hazard relating to dwellings located along the crest of the main escarpment (i.e. the west side of Oaia Road) that could be undermined by regression of the escarpment during future landslide events. This is to be included in a separate future study.

This report: has been prepared by GHD for Auckland Council and may only be used and relied on by Auckland Council for the purpose agreed between GHD and Auckland Council as set out in Section 1.2 of this report.

GHD otherwise disclaims responsibility to any person other than Auckland Council arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

B1.4 Report Structure

This report accompanies and informs numerous other assessments associated with the Muriwai landslides. A list of companion reports is presented in Table B1. A3 plans referred to in this report are listed in Table B2 and relevant additional images and data are presented in Appendices B-1, B-2, B-3 and B-4.

Table B1 Summary of accompanying Muriwai landslide risk assessment reports

Report Section	Description
Overall Report	Waitakere Coastal Communities Landslide Risk Assessment (Muriwai)
Appendix A	Figures
Appendix B	*Engineering Geological Report (this report)*
Appendix C	Slope Stability Assessment
Appendix D	RAMMS Debris Flow Analysis
Appendix E	Landslide Risk Assessment
Appendix F	Geotechnical Investigations Report

---

[2] In this report 'large scale' landslide hazards refers to landslides originating from the main escarpment that typically have a volume of more than about 50 m^3 with the potential to cause total or partial collapse of a dwelling.

Table B2 List of maps and images in Appendix A that are associated with this report.

Figure No.	Description
GENERAL SITE LAYOUT	
A101	STUDY AREA - OVERVIEW
ENGINEERING GEOLOGICAL PLANS	
A111	LEGEND
A112	OVERVIEW
A113 -A116	CLOSE-UP PLANS 1 - 4
CROSS SECTIONS	
A120	CROSS SECTION A-A’
A121	CROSS SECTION B-B’
A122	CROSS SECTION C-C’
A123	CROSS SECTION D-D’
A124	CROSS SECTION E-E’
GEOMORPHOLOGICAL LANDSLIDE ZONES	
A125	SLOPE RELIEF AND PROFILE COMPARISON PLAN
ELEVATION MODEL COMPARISON	
A126	ELEVATION COMPARISON BETWEEN 2016 AND 2023 LiDAR TOPOGRAPHIC SURVEYS
SLIP MECHANISM MODEL	
A127	2023 CYCLONE GABRIELLE LANDSLIDE MECHANISM MODEL - MURIWAI
A128	2023 CYCLONE GABRIELLE LANDSLIDE MECHANISM MODEL - PHOTO MARK-UP

B2. Methodology

B2.1 Data review

GHD received and sourced a variety pre-existing data to support the landslide risk assessments carried out within this report and supporting Appendices (Refer Section B1.4). A summary of this data including how and where it has been applied is given in Table B3 and discussed further below.

B2.1.1 Topographic data

Pre- and post-Cyclone Gabrielle topographic data from airborne LiDAR surveys were made available to GHD by AC and LINZ for this study for use in this report, the slope stability study (Appendix C) and RAMMS debris flow modelling (Appendix D). The spacing of data is 1 m, which is judged to be suitable for these purposes. We understand that the provided data had been processed to be 'bare earth', i.e. buildings and vegetation had been removed.

A comparison of pre- and post-Cyclone Gabrielle elevation data by GHD is presented in Figure A126 (see Appendix A). If the data were in spatial agreement, it is expected that areas that have not experienced any ground damage would have the same elevation. Landslides would exhibit a loss in elevation (i.e. a positive value in Figure A126) at the head of the feature and the debris flow runout would display a gain (i.e. a negative value in Figure A126). However, the comparison shows that, typically, areas in Muriwai not known to have experienced land damage exhibit a decrease in elevation post-Cyclone Gabrielle of up to 0.3 m and some localised undamaged areas of several square metres show a difference of more than 0.3 m. We therefore consider that data is accurate to ±0.3 m. We speculate that this may be due to one or more of the following reasons:

- The pre- and post-Cyclone Gabrielle datasets have been subject to different processing methods, particularly with respect to removal of vegetation.
- Different coverage areas and density of vegetation between 2016 and 2023.
- The 2023 landslides are typically unvegetated, allowing for accurate LiDAR.
- Erosion of the 2023 landslide surface between 14 February and 4 March 2023 (almost 3 weeks).

Further technical information regarding the data is described in Appendix B-5.

B2.1.2 Anecdotal community feedback

Anecdotal evidence from the occupants of an area can be a useful source of information to supplement and/or confirm formal evidence. The community contains many people who have resided in Muriwai for decades and some are multi-generational residents. GHD Engineering Geologists met with members of the public at the Muriwai Surf Club for two separate sessions on 28 May 2023 and then again on 2 and 3 September 2023.

Anecdotal testimony of residents was taken, with maps being referred to for identification of feature locations. Residents who were unable to participate with the in-person interviews were given the opportunity to email any information of importance to Auckland Council, which was forwarded to GHD. Appendix B-2 gives a generalised summary of the information, with some data appearing on Appendix A Figures A101 and A111-A116. We have not reproduced all names and addresses of contributors but have presented the common themes.

The September sessions were to provide clarification to residents by GHD and AC following the release of the draft version of this report and associated appended reports. There was a large response from the community from the draft release of this report, with additional observations and suggested amendments to the presented anecdotal information. The community's assistance was helpful, appreciated and used to help improve the report.

B2.1.3 Historical literature review

A review of published documents that relate to the landslide hazard in Muriwai is presented in Appendix B-3. Several of these discuss the 1965 and 2023 fatality-causing landslides. Several large flood events in the 1920s and 1930s are reported but, notably, no other damaging landslide events are described.

Table B3 Summary of received data

Data type	Owner	Detail	Quality and limitation	Application
Topographical survey	LINZ, Auckland Council (Appendix B-5 for details)	- 2016 LiDAR elevation model at 1 m point spacing from AC (pre-Cyclone Gabrielle) - 2016-2018 LiDAR elevation model at 1 m point spacing from LINZ (pre-Cyclone Gabrielle) - 2023 LiDAR elevation model at 1 m point spacing from AC (post-Cyclone Gabrielle)	- The two datasets were converted into Digital Terrain Models to derive topographical surfaces and contours - Figure A126 outlines a comparison between the two surfaces, showing the resolved volume difference. This indicates significant relative discrepancy, and potentially some distortion within each individual survey.	- The two datasets were converted into Digital Terrain Models to derive topographical surfaces and contours - The 2023 dataset has been used to inform GHD mapping in this report. - Pre and post-Cyclone Gabrielle data has been used to inform GHD slope stability (Appendix C) and RAMMS debris flow modelling (Appendix D).
Measured and estimated rainfall	Auckland Council (measured) and Met Service (estimated)	- Measured data from tipping bucket gauge 'TP-08' - Quantitative Precipitation Estimate (QPE) from Met Service	- Tipping bucket gauge TP-08 was damaged from flooding associated with the event and therefore did not provide continuous data over the course of the cyclone. - The QPE was generated from rainfall estimated off Met Services rain radar and used to derive rainfall accumulation and peak values. There is inherent uncertainty with this data given it is a quantitative derivative.	- Assessment of recurrence values assigned to the risk assessment (Appendix D). - General reference throughout this report and in comparison, with measured groundwater data (Appendix F)
Public bore records	Auckland Council legacy Consent Data	- Historical public bore records surrounding study area general vicinity - Records depth of bore, depth of measured groundwater level below ground level and date	- Unverified data, quality unknown	- General reference to support groundwater assessment (Section B4.3)
Historical aerial imagery	Aerial Photography: LINZ/ LGGA Satellite Imagery: Google	- Non continuous record since 1940, varying image scale - 1940 - 1975: Aerial photography - 2004 – 2023: Satellite imagery	- None-specific	- Illustrating past development and land use change across the study area and supporting discussions around overall geological characterisation pf he site. - Compiled in Appendix B-1 with relevant features marked.
Private property file data	Auckland Council	- Design and construction details of dwelling foundations and general property earthworks and stormwater/wastewater control	- Quality is variable dependant on completeness of data.	- Generally referred to in this report (Appendix B) to support understanding of any impact or otherwise from surface water drainage

B2.2 2023 – 2024 field investigations

B2.2.1 Geological field observations and measurements

Desktop and field-based mapping by GHD in 2023 and early 2024 collected discrete geological observational data over the whole study area. The mapping focused on definition of the extent and characterisation of the landslides. Associated engineering geological features such as springs and outcrops were also recorded. The data has been used to support the overall ground model interpretation and landslide characterisation and is reflected in Appendix A, Drawings A111 – 116, A120 – A127.

Landslides identified through the mapping process were catalogued in a register with common measurements included. This is attached as Appendix B-4.

The objective of the mapping was to:

- Confirm the location and extent of the February 2023 landslides.
- Record the observed exposed geology and geomorphological features.
- Inspect and assess pre-identified areas of geological interest (i.e. Edwin Mitchelson Track, geological outcrops, areas associated with anecdotal evidence).

The methodology included both desktop and field-based mapping:

1. Initial desktop mapping via QGIS and ArcMaps; identification and indexing of landslides using post-event topographical and photographic surveys; mapping of observable landforms and correlation with mapped geology.
    a. Initial site-based field mapping to ground truth the extent and nature of landslides (including their engineering geological properties), mapped geology extent and nature; assess geomorphological features and some man-made features (e.g. Edwin Mitchelson Track). This involved use of analogue (paper base maps) and digital techniques (ArcGIS FieldMaps) to collate GPS-tagged photographs and site notes;
2. Refinement and updating of final maps on desktop QGIS software following site-based data collection.
3. Further field mapping and updating of maps to include assessment of tension cracking adjacent to the escarpment crest (Oaia Road).

Site based mapping was carried out over the following dates:

- 24-26 May 2023: General mapping and classification of landslides, surficial geology and landforms surrounding escarpment
- 7 August 2023: Exploration for identification of tension cracking behind the escarpment crest.
- 30 Jan-15 Feb 2024: Further measurements of slope profile along escarpment crest.

B2.2.2 Subsurface geological investigations

Subsurface geotechnical investigations comprising nine rotary cored boreholes up to 80 metres deep, in-situ measurements, and installation of groundwater monitoring within constructed piezometer wells, were completed between 29th June and 17 August 2023. This was supported by a subsequent sampling and laboratory testing programme.

The investigations were intended to help develop an understanding of the ground conditions and groundwater regime in the vicinity of the site with particular emphasis on the material behind and below the escarpment. The data collected, including a detailed account of methodology of acquisition, calibration records and any reported error, is given in Appendix F (Geotechnical Investigations Report – Muriwai). The locations of the boreholes are shown on Figure A101 (Appendix A). Continuous telemetered groundwater monitoring of piezometers in six boreholes (BH-M01, M02, M03, M06, M07, M09) commenced from 19 October 2023.

B3. Study area description

B3.1 Nature and extent of the study area

Muriwai is situated on the west coast of Auckland at the north-western terminus of the Waitakere Ranges (see Figure B1 and Figure A101 (Appendix A). The site is defined by a near-continuous 1.5 km-long escarpment that is aligned to northeast – southwest. The escarpment face extends 80m vertically and is over 100 m above sea level at its crest. The town of Muriwai is built above and below it, including some properties directly at its base, and other directly on its crest. The landslides that have impacted Muriwai properties are predominantly located within this feature.

The crest of the escarpment is irregular along its length – some areas are inset further than others (Figure B1). Domain Crescent and Motutara Road are located within two larger inset areas and provide access to properties at the base of the escarpment. Oaia Road runs parallel to and setback from the crest and provides access to properties above the escarpment. Muriwai Beach, which comprises a long open coastline extending beyond the study area to the north, is accessed several hundred meters west of the escarpment, from which it is separated by sand dunes.

Current land use within and surrounding the site includes residential, isolated light commercial, recreational public land (beach frontage, regional park, and sand dunes), and private land (forestry and golf course).

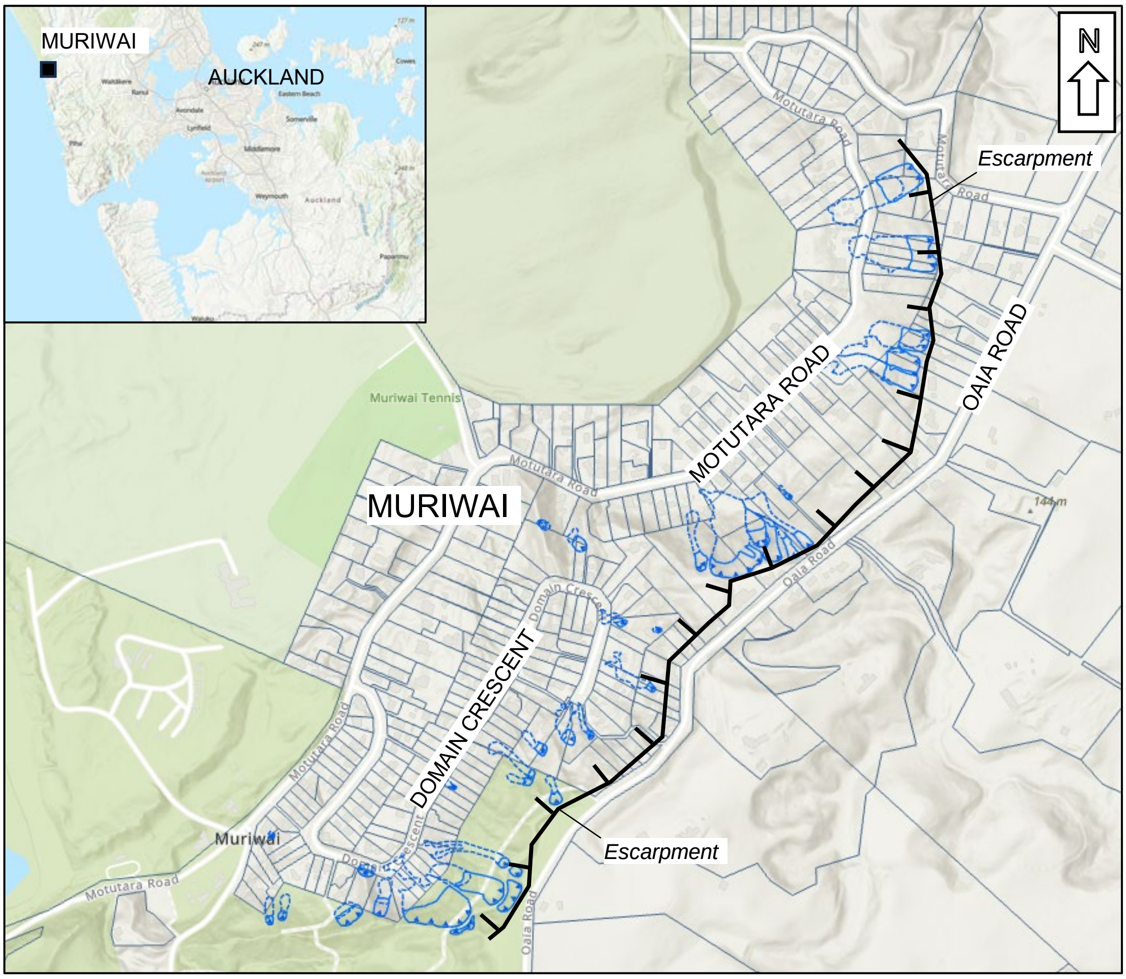


Figure B1 ***Muriwai location showing the February 2023 landslides mapped by GHD (blue lines)***

B3.2 Study area geology

B3.2.1 Stratigraphy

Figure B2 shows the geological setting of the study area. Most of the site is locally underlain by Awhitu Sand Formation. The stratigraphy in the study area is summarised below and in Table B4.

Figure B2 Excerpt from Hayward, B.W 1983: Sheet Q11, Waitakere. Geological Map if New Zealand 1:50,000. NZGS.

3.2.1.1 Mitiwai Sand

'Modern beach and drifting sand, and fixed dune sand', Hayward, (1983). The sand black and minerally rich (iron and titanium). In relation to the study area, these sands make up the dune systems northwest of its boundary and impacted dwellings from the landslides.

3.2.1.2 Awhitu Sand

'Coarse sand, clayey, often limonitised (iron cemented), with minor tuff, lignite and siltstone', Hayward (1983). The limonite imparts some strength, making the material weak to extremely weak sandstone, when unweathered. The material weathers to a sandy soil at the surface. The country that Awhitu Sands underlies is typically rolling flat terrain except for where the escarpment is located which is comprised of this material. The sandstone varies from a massive to a bedded structure and is cross bedded at roughly metre scale.

3.2.1.3 Waitakere Group

Three formations of the Waitakere Group volcanic/volcaniclastic deposits uncomfortably underly the Awhitu Sands, in the proximity of the study area. Nihotipu, Waiatarua and Tirikohua Formations underlie the Awhitu sands and outcrop at the surface south of Domain Crescent on Waitea Road.

- **Nihotupu Formation**: volcaniclastic sandstone, thinly bedded at shallow angles, often with discrete layers of course angular volcanic conglomerate. Outcrops south of the study area. Deposited concurrently and interlain with Waiatarua Formation.
- **Waiatarua Formation**: submarine basalt flows and pillow lavas. Columnar jointing common. Locally weathers to clay near the surface.
- **Tirikohua Formation**: volcaniclastic sandstone, bedded at shallow angles. Generally comprising finer grained material than Nihotupu Formation.

Table B4 Study area geological stratigraphy

GNS Group	GNS Formation	GNS symbol	Geological age (absolute)
Kaihu Group	**Mitiwai Sand, fixed dunes (qmf)**	qm qmf	Holocene, <10 Kya
	Awhitu Sand (qs)	qs	Pleistocene, <2 Mya
Regional unconformity			
Waitakere Group	**Tirikoha Formation (mt)**	mt	Late Miocene, ~ 5 Mya
	Waiatarua Formation (mw)	mw	Miocene, ~23 – 5 Mya
	Nihotupu Formation (mn)	mn	Miocene, ~23 – 5 Mya

Note: Stratigraphy as per Hayward, (1983), GNS 1:50,000 Map, Sheet Q11 Waitakere

B3.2.2 History and structure

From the late Miocene to Pleistocene, the geological history of the study area is broadly summarised as being subject to repeating cycle of deposition, erosion, uplift and further down-wearing of the Waitakere Group volcanic deposits (Hayward, 1979). From the Pleistocene onwards, the Awhitu Sand Formation has been deposited unconformably on-top of an erosional surface of the Waitakere Group (Nihotupu and Waiatura Formations at the study area) and as a result experienced similar uplift and down-wearing cycles. The uplift occurred on a series of faults that primarily strike Northeast and have formed 'blocks' of land that are upthrown and downthrown relative to each other (Hayward, 1976). This process has also resulted in shallow (10-15°) dip to the northeast along the unconformity, within the 'Maori Bay Block', as mapped immediately south of the study area (Figure B2).

Tirikohua Formation locally outcrops in the coastal cliff line southwest of the study area and is bounded by a fault that is mapped to continue to the northeast before losing its surface exposure at the southern extent of the study area (i.e. at Domain Crescent). It is unclear whether this fault continues to the northeast along the base of the escarpment.

B3.3 Surface characteristics

B3.3.1 Surface features

The top of the escarpment has a prominent scalloped nature, as shown in Figure B1, and combined with the presence of the irregular (hummocky) benches occupied by Motutara Road and Domain Crescent below the escarpment suggests that study area may have been subject to large-scale land sliding in the past. The mapping and drilling described in Section B2.2 were undertaken partly to investigate this possibility.

B3.3.2 Surface water catchments

There are approximately ten small catchments within the vicinity of the Muriwai escarpment and there are numerous surface water flow paths within these (see Figure B3). The surface water west of the escarpment flows to the west and the surface water at Oaia Road and surrounding properties flows to the northeast.

GHD (2023[1]) assessed the stormwater discharge from 35 properties between Oaia Road and the escarpment edge and demonstrated that the discharge from private properties drains towards Oaia Road and that the public stormwater system on Oaia Road is adequately sized and conveys flows away from the escarpment.

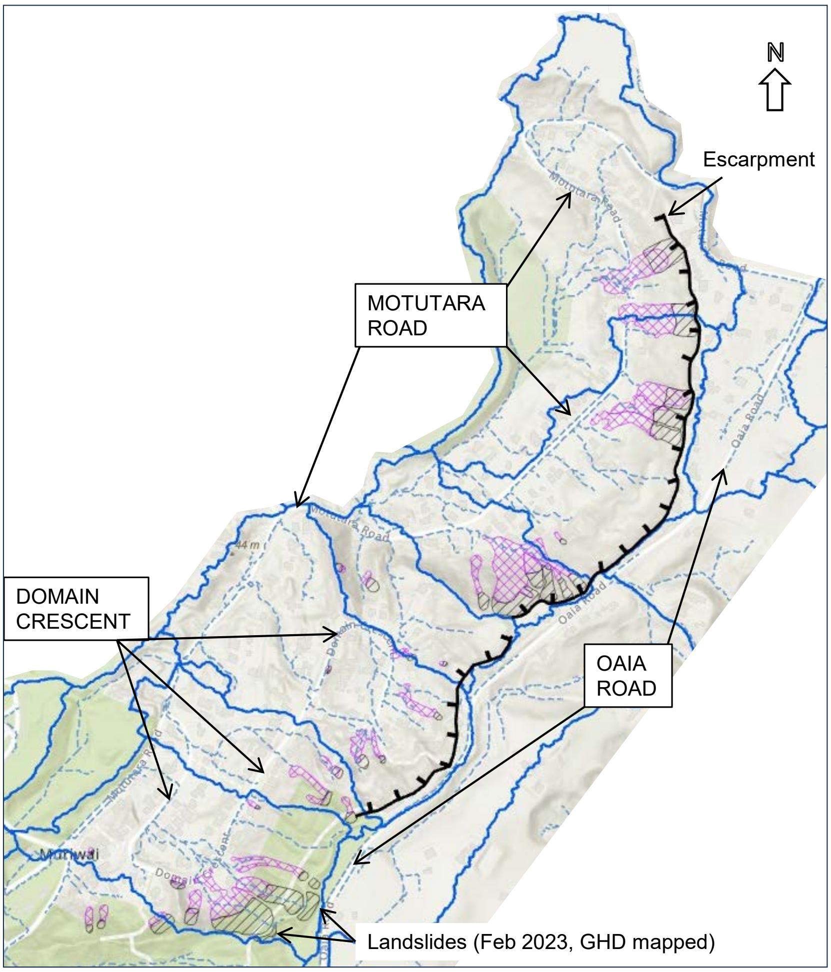


Figure B3 *Water catchments in Muriwai. Solid blue lines are individual catchments and thin blue dashed lines are nominal surface water flow paths. Defined by GHD using LINZ topographic data.*

B3.4 Historical land-use change

Appendix B-1 presents available historical aerial photographs and satellite imagery of the Muriwai area from 1940 through to 2023. A summary of the known land use and vegetation change since the early 1900s is given in Table B5.

Table B5 Land use change from early 1900s to the present day

Time period	Commentary
Early 1900s	- Refer to Figure B4 (view north from Edwin Mitchelson house) - Residential development began in the early 1900s with isolated dwellings accessed by Oaia Road and Edwin Mitchelson Track - Coastal/dune systems along Muriwai beach undeveloped and possibly lower in elevation
1940	- Motutara Road constructed, associated with more residential development and several community buildings near beach. - Escarpment is covered in low density scrub and medium sized vegetation. Some areas below escarpment have been recently cleared. Coastal sand dunes are unvegetated. - Exposed soil/rock noted near the crest and off leading ridgelines. - Surrounding countryside mainly cleared and predominantly agricultural land use.
1950 – 1975	- Domain Crescent, Waitea Road constructed, later followed by Coast Road (1975), associated with continual residential and commercial infill in these areas. Many sections still bare or utility structures only. - Muriwai Golf course constructed and local earthworks / contouring of land apparent. - Stormwater reservoir to the west of Motutara Road now constructed. - Pine plantation established northwest of Motutara Road, cleared and regrown.
1975 – present day	- Continual infilling of residential development both below and above escarpment - Wilding pine and native vegetation gradually increasing across escarpment to present day density.

Figure B4 *Early 1900s (unspecified), approximate location of present-day Edwin Michelson Track/Oaia Road, looking due North over Muriwai Beach. Source: Supplied by Auckland Council, 2023, Edwin Mitchelson House*

B3.5 1965 Landslide event

Two parallel landslides occurred on Domain Crescent on 27 and 28 August 1965, destroying two dwellings and killing two people. These landslides followed two days of unusually heavy rain, with a nearby gauge recording 95 mm on August 25 to 26, plus 45 mm in the 12 hours preceding the landslide that occurred on 27 August 1965 (Hayward, 1965). Elsewhere between 190 mm (Manukau Heads) and 220 mm (Whenuapai) was recorded over the 3-day period. The two landslides were reported as fast-travelling mud slides by witnesses. Many additional smaller landslides occurred over the wider area for several days after the rain event (Wright, 1996). The headscarp of the two larger landslides was located directly below Edwin Michelson Track. Various reports at the time suggested they were triggered by excessive surface water being diverted off the track resulting from blocked table drains (Hayward, 2022). Wright (1966) observed that for days after the events water seeped out of the Awhitu Sand about midway up the landslide paths. Hayward (2022) concluded that the landslides were likely triggered by a combination of the surface water flows and the groundwater springs.

The two separate debris paths coalesced near the bottom of the escarpment and flowed across Domain Crescent (Figure B5 and Figure B6). Both the destroyed dwellings were located on the uphill side of the road and were translated with the debris flow.

Five dwellings have since been constructed at the site of the 1965 landslides. A series of new landslides occurred at the same location resulting from the 2023 ex-tropical cyclones.

Figure B5 Mapped extent of 1965 Landslides (after Wright 1966)

Figure B6 View from Domain Crescent of 1965 landslides and destroyed dwellings (after Wright 1966)

B3.6 Overview of February 2023 landslides

The February 2023 landslides occurred along the Muriwai Escarpment within Awhitu Formation sand and silt, above the Domain Cresent and Motutara Road benches, and from several leading ridgelines between. The locations of all recorded landslides are given in Figure A101 (see Appendix A). Examples of the damage associated with the runout are given in Figure B7 and Figure B8. Key details of the event are summarised as:

- Most landslides originated near the crest of the escarpment on the evening of the 14th February 2023 (peak rainfall intensity), travelling down the face and terminating at or close to the base. Most landslides were greater than 50 m^3 of material released and often entrained large amounts of vegetation, including trees.
- The material was saturated and flowed at significant speed, giving little to no warning.
- Significant damage and destruction (including complete collapse) of impacted residential structures occurred, contributing to two fatalities. In addition:
  - Some properties above the landslides (accessed from Oaia Road) were partially undermined from the loss of material.

        - Various damage to non-residential structures also occurred (commercial buildings; AC property; walking tracks)
- On-going erosion after the event resulted in the repeated blocking of public table drains in road corridors.
- Many new groundwater springs were observed to be emitting constant flow after the event.

***Figure B7** Entrained vegetation and sand/silt comprising the overall 'colluvial debris', GHD 2023. Debris resulting from Landslides M-LS07,08,09.*

***Figure B8** Example of significant destruction of dwelling, associated with landslide debris runout, GHD 2023. Debris resulting from Landslides M-LS12.*

B4. Engineering geological interpretation

This section of the report explains the development of the engineering geological model of the site area from analysis of the available geological, geomorphological, groundwater and surface water data.

B4.1 Geological units

Engineering geological units were developed from the GNS mapped geology (Table B4) and the site investigation data (Appendix F) to support the ground interpretation and landslide assessments of the study area. The information is presented as follows:

- Table B6 summarises the geological unit characteristics and defining features.
- Illustrations of examples of the units as recovered in borehole core and/or observed in outcrop are given in photo figures below the table.
- Interpretation of the surface distribution of the units is given on the Engineering Geological Maps (Appendix A, Figures A111 – A116).
- Interpretation of the sub-surface distribution of the units is given in the Engineering Geological Cross Sections (Appendix A, Figures A120 - 124).

B4.2 Geomorphology

The study area has been divided geomorphologically into six landslide 'zones' based on the surface topography, February 2023 landslide characteristics and general geomorphology. The purpose of this is to differentiate areas according to their susceptibility of large-scale landsliding. The geomorphological zones are shown on the attached engineering geological maps (Appendix A, Figures A111 – A116) and the basis for the zoning and the zone characteristics are described in Section B6.3.

Table B6 Engineering geological units

GNS Formation	Engineering geological unit	General description / comments	In-situ strength characterises	Occurrence across study area	Example photo figures
N/A	**Recent Colluvium (2023)**	- Orange to pale yellow, uncemented and unconsolidated sand, varying level of silt intermixed. Usually entrained with surficial vegetation debris and topsoil. - Still consolidated/cemented blocks near source (headscarp) which are partially broken down - No discernible structure or internal fabric - Easily eroded / dispersed by surface water - Sourced from Less Cemented Sand unit	- No measurable strength - Inferred as very loose, with friction angle of less than 10°.	Within mapped landslide, usually collected at the base of the escarpment along Domain Crescent and Motutara Road. Some material still preserved on escarpment face.	-Figure B7 -Figure B8 -Figure B9
	Fill Deposits	- Orange, brown clayey silt, mixed with topsoil - Less than 1 m thick where encountered	- Single shear vane value > 100 kPa	Encountered locally within single borehole (BH-M02) however inferred to be present across study area in discrete and small volumes (<50 m^3) to support residential, building platforms, localised road fill	-Figure B10
	Ancient Colluvial & Alluvial Deposits	- Chaotic’ texture with irregular shaped clasts of silty and clayey material - Varying degrees of organic material - Often significant (more than 1 m) inclusions of ‘intact’ Awhitu formation sand, cross bedded - Sharp and irregular boundaries between varying textures/types of material - Within BH-M06, potentially contains alluvial materials as well as colluvial sourced material	- Variable, generally characterised by: - SPT ‘N’ value 0 to <20	Encountered to varying depths within boreholes: - BH-M05, BH-M07, BH-M08, up to 7.5mbgl. - BH-M06, up to 38 mbgl Lateral extent between boreholes poorly constrained.	-Figure B11 -Figure B12
Awhitu Sand Formation (qs)	**AS: Less Cemented Sands** ***Includes discrete layers of:*** ***- ASf: Organic Soil / Peat*** ***- ASf: Silt/ Clay***	- Variable coloured and weathered, generally orange, light yellow, or cream white at surface, and orange to grey below surface - Uniformly graded medium to coarse sand - Some cement (evident by in-situ density) although often recovered as unconsolidated and dilated in core - Discrete layers of limonitic material - Crossbedding common at a sub-metre scale with laminated layers 0.1 m thick, with no visible preferred orientation. - Bedded to massive, beds 1-2 m thick separated by thinner (<1.0 m) layers of finer grained material. In outcrop, beds display near horizontal, slight northward dip. Non-continuous. - Jointing vertical and tight, develops moderately sized blocks <1m3 near crest Escarpment - Occasional occurrences of thin layers/lenses (<1.0 m thick) of finer grained silt, and peat - Prone to erosion (‘dispersibility’) and possible tunnel gully erosion based on the results of Pinhole and crumb testing results (Appendix F, Section F4.5). Note – no direct evidence of tunnel gully erosion has been observed during GHD site investigations, or within previously documented studies.	- SPT ‘N’ value 0 – 20, generally unchanging with depth, some variability with more cemented sand layers. - UCS <1 MPa - Peat and silt/clay layers unmeasured, inferred: -SPT ‘N’ value = <10 -Vane Shar strength = <50kPa	- Surficial deposit over majority of study area, exposed within the slip face of most recent landslides. - Generally encountered to 20-30 m bgl before transitioning into cemented sands/candstone (below) - Bedding and crossbedding observed in outcrop in many landslide source areas - Layers of silt and clay observed in outcrop and often extending up to 100 m laterally at surface, 1.0 m thick - Peat layers rarely encountered and not traceable laterally.	-Figure B13 (cross bedding -Figure B14 (less cemented sand) -Figure B15 (interbedded sand and silt layers) -Figure B16 (silt/clay layer) -Figure B17 (peat/organic soil)
	AS: Cemented Sand / Very weak Sandstone ***Includes discrete layers of:*** ***- ASf: Organic Soil / Peat*** ***- ASf: Silt/ Clay***	- Generally dark orange, - Variably weathered (slightly to moderate), extremely weak to weak, iron cemented Sandstone. Massive to bedded. - Presence of more cement than the overlying less cemented material is inferred to be responsible for the increase in in-situ strength. - Uniform (coarse) grained sand clasts - Similar but better preserved fabric as overlying less cemented material: - Cross bedding <1m scale, horizontally bedded (interbedded with finer grained material) - Irregular occurrences of limonite layers	- SPT ‘N’ Value = 50+ - UCS >1 MPa, to >2 MPa	Not encountered in outcrop / at surface, generally 20-30 m and deeper below local ground level	Figure B18
Nihotupu Formation (mn)	**N: Residual Silty Clay**	- Dark red and brown, very stiff clayey silt and gravelly silt. - Irregular limonite staining - Relic rock texture visible	- Vane shear strength = >100 kPa - SPT ‘N’ Value = 17-22	Encountered south of study area at surface, in outcrop (Awatere Road). Within study area, encountered in BH-M04 from surface (below road fill).	Figure B19

*__Note:__ **Mitiwai Sand Formation** is referred to in Section B2.2.1.1 and included within Appendix A figures for general reference, where indicated by Hayward (1983) mapping. It has not been assessed from an engineering geological perspective as it is not encountered within the study area at the surface / sub-surface. It is not considered relevant to the observed landslides that have occurred on the escarpment face.*

Figure B9 *Example of engineering geological unit '2023 Recent Colluvium'. Medium grained sand, unconsolidated, spread out thinly across existing surfaces.*

Figure B10 *'Fill Deposits' soil recovered in BH - M02: 0.0-1.5 mbgl*

Figure B11 *'Ancient Colluvial/Alluvial' soils recovered from BH-M07: 3.65-5.34 mbgl*

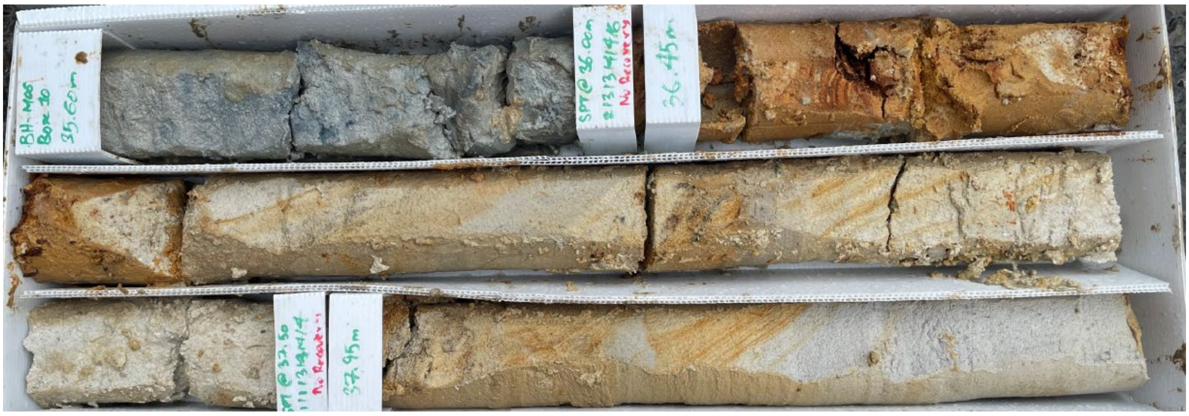


Figure B12 Example of in-situ 'blocks' of cross-bedded Awhitu Formation within Ancient Colluvial/Alluvial soils, from BH-M06: 36.45-38.2 mbgl

Figure B13 Outcrop of Awhitu Sand Formation - Less Cemented Sands, cross bedding evident (left). Exposed within 2023 landslide, Domain Crescent.

Figure B14 Example of Awhitu Formation Less Cemented Sands, weakly consolidated material from BH-M02, 11.6-14.7 mbgl

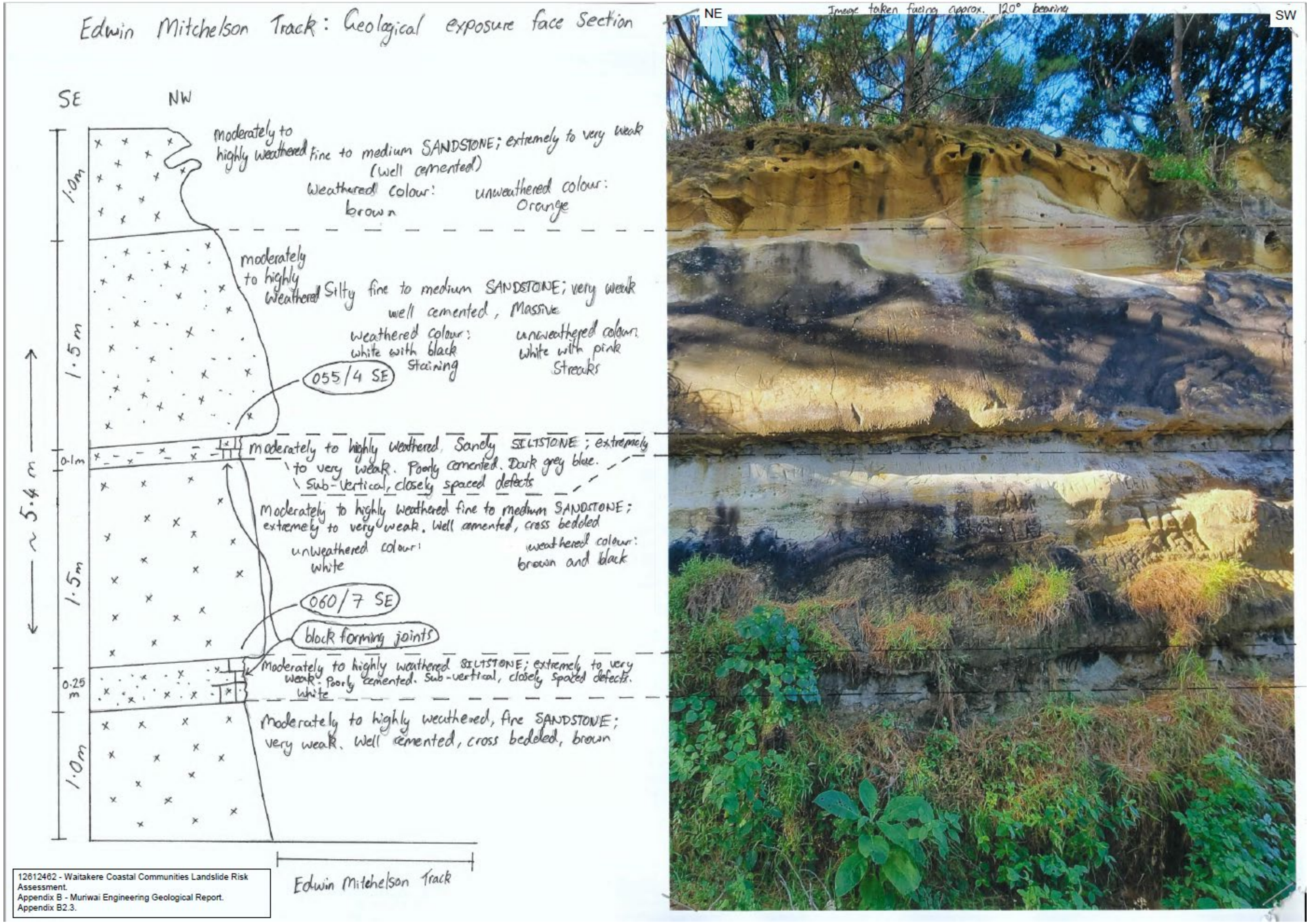


Figure B15 Face log of Awhitu Formation Less Cemented Sands preserving rock fabric and structure, Edwin Mitchelson Track cut slope. Refer Figure A116 for specific location (marked).

Figure B16 *Outcrop of Awhitu Formation – Less Cemented Sands, layer of finer grained material (silt, clay). Approximate thickness 1 m.*

Figure B17 *Example of layer of peat/organic soil within Awhitu Formation Less Cemented and Cemented Sandstones, from BH-M02, between 7.95 8.75 m bgl.*

Figure B18 *Example of Awhitu Formation Cemented very weak Sandstone, oxidised, from BH-M02 36.65-37.5 mbgl*

Figure B19 Example of Nihotupu Formation Residual Silt and Clay, from BH-M04 3.95-5.90 mbgl

B4.3 Groundwater

B4.3.1 Data

Table B7 summarises the available groundwater data and our assessment of this data.

Table B7 Summary of groundwater data reviewed and observations

Data	Comment	Example / reference
Surface seeps/springs	Springs have been observed and mapped across the escarpment (Figure A112-116). Where the source of seepage was observed directly it was commonly located above finer grained silt/clay beds and more oxidised/cemented layers (limonite).	Figure B20 Figure B21
Variable head permeability testing	Hydraulic conductivity values measured within BH-M01, M02, M06 and M07 (E-08 to E-09) are considered typical for the material that their respective screens are constructed within (massive sandstone, M01, M02, M07) and silt/clay soil (M06).	Appendix F, Table F6
On-going groundwater level monitoring	Continuous groundwater level monitoring established in six piezometers since 19 October 2023 (BH-M01, M02, M03, M06, M07, M09). - Refer discussion below, assumed error within BH-M01 and M09 - BH-M03 has been dry since shortly after installation. - Generally little to no connection observed between recorded rainfall and groundwater level, except for: -- BH-M06: positive correlation when peak daily rainfall exceeds approximately 12 mm/day. Fluctuation in groundwater level relatively short, generally +/- 2 mbgl for 1-2 days following peak rainfall. -- BH-M07: weak correlation when peak daily rainfall exceeds approximately 15mm/day, corresponding groundwater level fluctuation of less than 0.5 m, with very gradual return to baseline level (2-3 weeks). - Generally stable / unchanging monthly average values, no seasonal variation observed.	Section F3.3.3 Appendix F5 (groundwater vs rainfall graphs)

Data	Comment	Example / reference
Electronic dip-tape measurements	Sporadic measurements to calibrate telemetered data. Minor variance in measurements, considered insignificant to trend observed in telemetry.	Appendix F, Table F5
Legacy bore records – groundwater levels (AC)	3 bores installed surrounding the project area. #21261 and #22794 record significantly deeper groundwater levels (120-129 mRL than adjacent GHD piezometer BH-M01 (approximately 80 m vertical RL difference). GWL at BH-M03 is unclear given well is dry. Recorded geology at screen suggests bore is socketed into underlying Waitakere Group deposits.	Figure B22

Data limitations

- Piezometer BH-M01 data is considered invalid (erroneous) given both the 'erratic' nature of day to day changes in recorded groundwater level and the two significant sudden changes of approximately +/- 8 m vertically over 24 hr time periods that are uncorrelated to measured rainfall. The telemetry unit and data have been inspected for any obvious physical or recording errors/damage, however none were revealed.
- Piezometer BH0M09 data is considered as potentially invalid given the recorded groundwater level is physically unchanged over the recorded interval expect for one brief (<24 hr) change in late November before returning to the constant reading approximately 7.6 mbgl.

Figure B20 Groundwater seepage above highly oxidised (limonite) layer within Awhitu Formation 'less cemented' sand

Figure B21 *Groundwater spring emitting above silt/clay bed within Awhitu Formation 'less cemented' sand.*

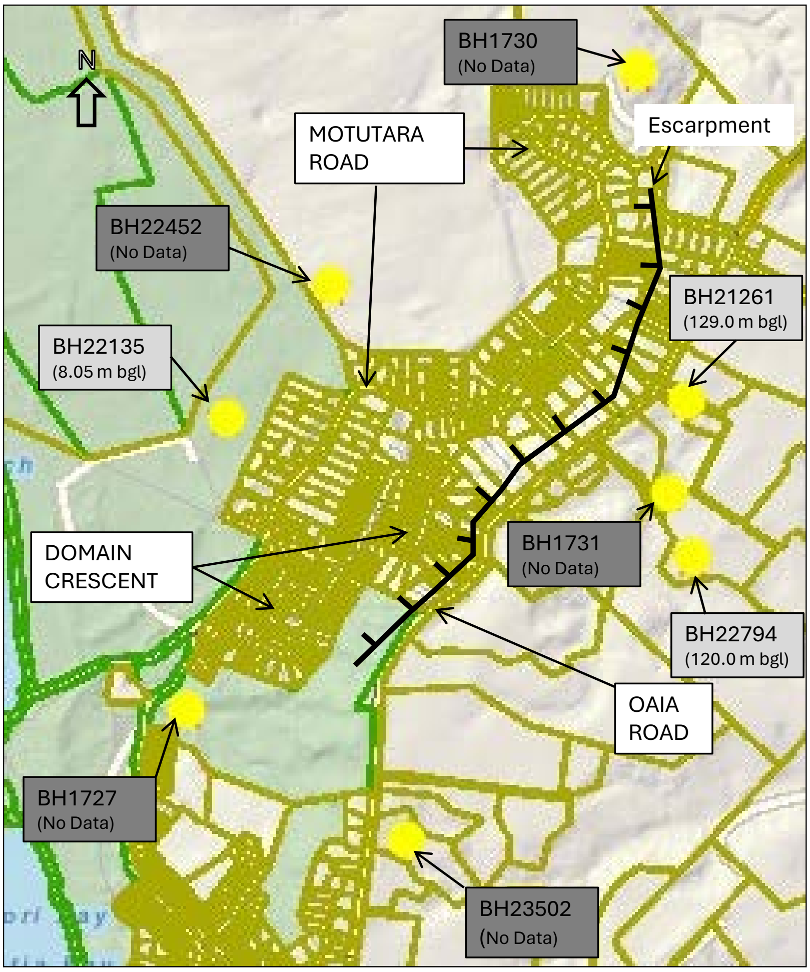


Figure B22 *Historical well location plan with water level, where known (measured between 2004 and 2007). Supplied by AC.*

B4.3.2 Groundwater interpretation

From the subsurface and surface groundwater data/observations, it is inferred that:

- A ‘regional’ groundwater table is located within Awhitu Formation sands, at or above the unconformity with underlying Waitakere Group Deposits, which are expected to represent a significant change (decrease) in relative permeability.
    - Historical data (Figure B22) suggests Waitakere Group may have been encountered east of the escarpment, at an RL approximately 30-40 m below its base elevation. The unconformity was not encountered below the study area other than at the southern end, in BH-M04.
    - It is unlikely that this regional groundwater table has any influence on the groundwater recorded in the study area.
    - All piezometers installed by GHD are located within overlying Awhitu Group deposits and record perched groundwater levels at significantly higher elevations.
- The Awhitu Formation sands contain a series of perched aquifers, some of which daylight as springs within the escarpment and that have variable (often none to minimal) connection to surface rainwater input.
    - They are bounded by discontinuous, relatively lower permeability layers/beds of silt/clay and limonite within the Awhitu Formation sands. The continuity of the aquifers is therefore a function of these layers/beds.

The relationship between the local groundwater level and pressure in the perched aquifers during peak or long duration rain events (such as Cyclone Gabrielle) is uncertain given there is no continuous subsurface data to date across an event of this magnitude. It is judged that the vertical and horizontal flow of groundwater within the Awhitu Formation sands is highly variable across spatial and temporal domains. Individual perched aquifers may be influenced by surface rainfall infiltration. It is also possible that, following the 2023 landslides, shallow perched aquifers have been destroyed or modified because of loss of overlying soils. This is partly supported by anecdotal observations of changes at springs from residents.

B4.4 Surface water

The escarpment is a significant barrier to the direction that surface water flows across the study area. Rainwater collects and flows due east above/behind the escarpment and due west within or below the escarpment.

Within the escarpment, flow paths are further controlled and concentrated by the smaller catchments defined by confining ridgelines and spurs, generally at right angles to the slope. These are summarised in Figure B3 for the study area.

The built environment of the local area, both above and below the escarpment, has resulted in the addition of impermeable land cover (hardstands/driveways, houses) and diversion of three waters (stormwater and septic water lines from residential property and stormwater drainage within public and private roads). The potential for any of these built structures to influence the natural surface water flow paths was assessed by reviewing AC supplied information for thirty-five properties located on Oaia and Motutara Road, as well as the stormwater catchment system within Oaia Road (GHD 2023 ‘Desktop Assessment Report’; GHD 2023 ‘Oaia Road and Edwin Mitchelson track Investigation Report’). It was concluded that:

- None of the private property stormwater / wastewater discharge was directed toward the observed landslides or damaged by them, except for 225 Oaia Road
- The existing stormwater catchment system on Oaia Road is adequately sized and draining away from (east of) the escarpment crest
- The table drains along Edwin Mitchelson track have been blocked by landslide debris.

Thus, GHD do not consider there to be any evidence for instigation or worsening of any observed 2023 landslides from built structures, from the available data reviewed.

B4.5 Ground model of study area

B4.5.1 Distribution of geological units

The surface morphology of the study area is the result of it being uplifted and tilted to the north-east unconformity of the underlying Waitakere Group deposits (Section B3.2.2). Nihotupu and Waiatarua Formations outcrop directly south of the study area (see Figure A114), but dip below the surface to the northeast and were not encountered at surface or at depth (beyond the location of BH-M04). Awhitu Sand Formation has been deposited and uplifted on top of this contact, thus sharing similar structural orientation, evident from silt/clay beds in outcrop (see Figure B23).

Previous studies (Hayward, 2022; Wright 1966) have suggested Waitakere Group deposits were located directly at the base of the escarpment however GHD’s 2023 ground investigations and mapping do not provide evidence for this. The unconformity is illustrated on cross-section A-A’ (see Figure A120).

B4.5.2 Material properties, Awhitu Sand

The in-situ strength profile of the Awhitu Sand formation increases with depth, observed from increasing SPT ‘N’ values within boreholes. This is interpreted to be the result of increasing quantities of iron cement within the sand and leaching associated with the development of an in-situ weathering profile from the surface. Engineering geological cross-sections (see Figures A120-124) illustrate this with the inferred boundary between less cemented and more cemented sands/sandstones. Significant uncertainty in spatial constraint of this zone is expected, given the lack of subsurface data points available.

Recently exposed sands (landslide slip surfaces) often retain near-vertical bluffs and rock mass fabric (block jointing and bedding, Figure B15); however, it is easily disrupted when physically agitated or when water is passed through it, as observed by sections of shallow core having disaggregated upon recovery. This is not observed with core at depth.

Silt/clay rich beds and thinner lenses are encountered randomly at depth with poorly defined lateral connection. They are not interpreted to be continuous over the study area however are observed to extend at least 100 m laterally approximately (Figure B23). These layers are often associated with areas of flatter slope profile, illustrated as ‘mid-slope benches’ on Figures A112-116. Organic layers are less common and only observed as <1.0m layers/lenses within borehole core (Figure B17).

B4.5.3 Groundwater

There is likely a deep regional water table (probably draining to sea level) well below the escarpment. The silt/clay beds within the Awhitu Sand influence groundwater movement and result in localised perched aquifers some of which are directly affected by rainfall (Section B4.3).

B4.5.4 Surficial deposits

Ancient deposits of colluvium (and potentially intermixed alluvium) are present at the base of the escarpment along sections of Domain Crescent and Motutara Road (Figure B11 and Figure B12; Table B6). An interpretation of their spatial extent, based on where the material was recovered within boreholes, is given in Figures A114,115,112 and 123. It is acknowledged that there is uncertainty with the extent of this material given the limited data points.

A graphical interpretation has not been given surrounding BH-M06 (Figure A122) due to the unknown lateral extent of the deep pocket of material encountered there (to at least 38 mbgl). Two interpretations are considered plausible:

- It represents a localised paleo-gully’ formed from a different sea level than present and has since been infilled by colluvial, alluvial and possible marine sources over time.
- It is a remnant of debris from a much larger ancient landslide that may encompass the northern area of Domain Crescent and explain the local higher elevation and irregular topography, possibly extending south of BH-M05.

The uncertainties associated with the nature and distribution of this material are not directly relevant to the scope of this assessment as it is not involved in any landslides associated with Cyclone Gabrielle. For this reason, it has not been considered further.

Figure B23 *Example of lateral extent of near horizontal silt/clay beds within Awhitu Group, indicated by dashed line. Domain Crescent, M-LS20B for reference. Gentle dip due north – northeast.*

B4.6 Conceptual landslide model

B4.6.1 Mechanism and controls

The mechanism proposed for the shallow translational landslides that transition to high velocity debris flows is illustrated in Figures A127 and A128 and summarised as:

- Intense and prolonged rainfall delivers significant volumes of surface water into the valleys of the catchments along the escarpment slope. The water is sourced from overflow along the crest as well as directly intercepted by the catchment. An unknown (but possibly not insignificant) amount of groundwater saturates discrete areas of the slope from surface springs emitting from local perched aquifers within the Awhitu Formation.
- A relatively thin surficial layer of less cemented sands and historical colluvium rapidly becomes saturated through infiltration by surface runoff and groundwater. The surficial sandy soil layer weakens from rapid loss of cement.
- At a certain point (within minutes or hours depending on rainfall and runoff intensity) the weight and pore pressure within the already weakened layer cannot be sustained and a planar shear surface develops at the base of this zone (typically less than 1.5 m deep). This process may be accelerated by the innate erosive/dispersive nature of the Awhitu Formation. The slip surface often undermines shallow rooted vegetation and larger pine trees that were previously providing a degree of structural support to the surface soil but now become entrained.
- The high-water content of the surficial materials causes them to lose internal strength and flow downslope rapidly as a debris flow.

- Finer grained silt and clay layers within the Awhitu Formation that have a higher degree of cohesion may experience preferentially less infiltration and be less impacted by cementation loss, and in turn resist shear surfaces developing. This may cause the surface to ‘break out’ over the top and flow over otherwise in-situ soil and vegetation that then becomes entrained and transported downslope.
- Additions of relatively intact, less cemented sandstone blocks from isolated rockfalls on the upper escarpment are also released, inferred to be the result of pore pressure developing between near-surface joints and bedding layers, and carried downslope within the debris flow.

The mechanism proposed is supported by observational data across the study area, from the 1965 and recent 2023 events. Deeper seated landslides that may develop along circular slip surfaces (for example) have not been observed during either the 1965 or 2023 events within the escarpment study area and Awhitu Formation Sands geology. Deep seated rotational landslides from water driven events are therefore not considered possible at this site. This does not necessarily preclude the possibility of deep-seated earthquake-induced landslides on a larger scale than those caused by Cyclone Gabrielle, however the observation and assessment of these are outside of the scope of this assessment.

B4.6.2 Uncertainties of landslide mechanism

Identified uncertainty or unknown processes and factors associated with the proposed mechanism of landslide development are:

- **Relative influence of surface vs groundwater in slip development:** Others (Wright, 1966; Hayward, 2022) have stated that groundwater fluctuations and spring emittance played a significant role within the 1965 landslides and by deduction this inference could be extended to the 2023 events. The especially wet summer season of 2023-2024 may have contributed to overall wetter soils and a relatively higher groundwater table. We do not disagree with this. However, without a continuous monitoring record of groundwater levels and rainfall prior to and during the landslide events, it is not possible to determine their relative proportional impact. Anecdotal commentary associated with springs along the face is difficult to rely on given the time of the event (night) and already significant volumes of surface/sheet flow that would affect the reliability of observations. We suggest that surface water (rainfall and runoff) during the event had the predominant impact based on the groundwater data collected to date which indicates only minor fluctuations following subsequent rain events.
- **Landslide reactivation and retreat ‘lifecycle’ across escarpment:** Recently failed areas now expose fresher more intact material within the slip face and are therefore less likely to generate future large landslides compared with neighbouring catchments which did not recently experience them and thus have a greater layer of weaker surficial material. It is possible that other factors would still have greater influence of the location and frequency of landslide occurrence, for example: size of confining catchment, slope angle, density of springs. The recurrence of significant landslide activity in 2023 at the same location as the two large landslides of 1965 must also be considered. Without sufficient record of multiple large events like this, preferential retreat/erosion cycles in one section of escarpment vs another is plausible, but unknown.
- **Removal of native fauna and/or replacement with exotics:** Accompanying the development of the Muriwai community native vegetation has been removed and replaced by exotic species (mainly pine trees). The latter are particularly prominent along the crest of the escarpment as wildling pines, which were commonly observed to be entrained within slip debris and in some cases increased the hazard of the landslides given their destructive force on built structures. It is not clear whether the addition of pine trees on the slope increased the probability of landslide development, but it is considered possible given they are significantly heavier than most surrounding native vegetation and are prone to windfall due to their shallow root systems.

B5. Characterisation of landslide hazard

B5.1 Morphology

Refer to Appendix B-4 which catalogues the main features of all landslides mapped in 2023. Dimensional values of the landslides are given in Table B8. Estimated volumes and (run-out) lengths are also reproduced in Table B9.

We have used the following terminology, which is in broad accordance with that of Hungr et al (2014).

B5.1.1 Definition of landslide type(s)

The landslides mapped on the Muriwai escarpment are *shallow translational slide movements* within Less Cemented Awhitu Formation sands. Once mobilised, they develop into *high-speed debris flows* down steep slopes (approximately more than 45° typical) until arresting at or near the base where they either encounter flatter topography or an existing dwelling, or both.

- There are often instances of rockfall that releases from near-vertical bluffs formed by some of the larger landslides main scarp (headscarp), resulting from apparent near-surface rock mass jointing within the Awhitu Formation material that creates blocks of less than 1m3 volume.

B5.1.2 Shape and size characteristics

- Usually have a relatively large run-out length compared with the width at the main scarp, consistent with typical debris flows. Less common, smaller landslides of less than 50 m^3 recorded with runouts of similar values to their widths. Figure B24 and Figure B25 show typical examples of the shape and size of single landslides, and merged larger landslide areas, respectively.
- The landslides expose less cemented Awhitu Formation sands with silt and clay beds, along the sliding surface (Figure B23). The height of observed main scarps and corresponding depth of slip surface relative to the pre-existing ground profile was observed during field mapping to be between 0.5 m and 1.5 m.
- Tension cracks above the crest of the escarpment and headscarps of the larger landslides were not generally observed in field mapping. Some evidence of these was observed in several properties along Oaia Road, however it is unclear if these were present before the event. In these instances, the observed cracking is close to the escarpment crest and thus may represent local relaxation and toppling of the material at the crest.
- Figure A126 shows that within the larger slides the average depth of the depletion zone (above the slip surface) is quite variable. Similarly, the zone of accumulation varies in thickness. Note the limitations with the data to develop Figure A126 is described in Appendix B-5.

Table B8 Summarised dimensional values (size and shape) of 2023 landslides

Summarised values for 2023 landslides	Main headscarp width (m)	Debris runout (m)
Average	**22**	**48**
Maximum	96	137
Minimum	4	8
Standard deviation (1)	19	36

B5.1.3 Distribution

- Most landslides originate (and form their main headscarp) near the crest of the escarpment and travel slightly beyond its base, with the largest slides traversing the full length (distance) to Motutara Road. Smaller slips originate within the escarpment or the main spurs from it.

- There are four distinct areas along the escarpment where landslide activity was more concentrated and debris fields merged. These are illustrated in Figure A126.

B5.1.4 Debris

- The debris is a mixture of residual soil and Less Cemented Awhitu Formation sand, silt, and clay, with ‘blocks’ of less cemented sandstone, entrained surficial vegetation and debris from impacted dwellings.
- The volume of debris accumulated at the base of the slopes tends to be a function of the confining catchment, with some debris fields being the merging of many separate depletion zones and in some cases originating from areas with merged head scarps (see Figure B25). The risk associated with this merging is addressed in Appendix D.
- The fluid nature of the debris flow means its travel path is strongly governed by the encompassing catchment / topography. This creates inconsistency in the spread of damage to the built environment at the base of the escarpment slopes.
- Field-based observations of inflicted damage suggest that debris travel velocities were ‘very rapid to extremely rapid’ (3 m/min to greater than 5 m/s; in accordance with Cruden & Varnes, 1996, ‘Figure 3-17’ and ‘Table 3-5’). Anecdotal evidence broadly agrees with these estimates.
- Silt and fines carried in solution during initial failure and deposition were re-mobilised periodically following later rain events.
- The cemented blocks from the isolated rockfalls typically disintegrated into the larger debris flow but occasionally reached the toe of the extent of the run out without being destroyed (e.g. landslides M-LS03, M-LS04, M-LS04a, see Figure A114)
- There is general uncertainty and expected error in the exact definition of the point of inflection between the depletion compared with the accumulation zones within each landslide given the colluvial debris are often observed to begin depositing part way up the landslide face in a thin veneer. This is difficult to map accurately.

Figure B24 *Typical features of single landslides* ***areas.***

Figure B25 ***Typical features of larger, merged landslide areas.***

B5.1.5 Frequency of occurrence

The rainfall data presented by AC (Table B3 *'Measured and estimated rainfall'*) indicates a peak rainfall total for Muriwai during the Cyclone Gabrielle event of 146.9 mm, occurring over 12-hour period. This total is >100-year event at a 12-hour duration. The data suggests that for the 12-hour duration rainfall the Annual Recurrence Interval (ARI) is >100 years and may be in the order of 250 years. However, we understand that the calculation above the 100-year assessment becomes increasingly unreliable, primarily because of the relatively short statistical rainfall records available in New Zealand. For the other durations modelled, the rainfall was below the 100-year event.

For the risk assessment discussed in the Appendix E report we have assumed that the annual likelihood of a landslide event that is similar in magnitude to the February 2023 event is about 1 in 100 (i.e., 0.01). The assumption of 1 in 100 based on rainfall frequency is a simplifying and possibly conservative assumption that we consider reasonable. It does not consider other factors that could potentially affect stability (antecedent conditions, geology, groundwater conditions, slope height and angle, vegetation, surface water management- overland flow path, overflow from water storage tanks, effect of effluent disposal field) all of which vary between locations and are difficult to quantify.

Based on discussions with AC, we understand that no reliable storm ARI value is available for the 1965 landslide event due to the lack of data. Hayward (2022) states that the 1965 landslides followed 2 days of unusually heavy rain, with a nearby gauge recording 95 mm on August 25 to 26, plus 45 mm in the 12 hours preceding the landslides that occurred on 27 August 1965. However, the author goes on to mention that this is somewhat less than that recorded officially for the 3-day period at Whenuapai (220 mm) and Manukau Heads (190 mm). Review of publicly available NIWA rainfall data suggests the ARI for a day-day rainfall event of similar magnitude is less than 100mm. The 1965 landslide event affected a considerably smaller area of the Muriwai escarpment than the recent 2023 event, suggesting that the triggering rainfall event was smaller. Considering the uncertainties above, we have assumed that a rainfall event with an ARI of about 50 (assuming current climate conditions) could trigger a similar landslide event to that experienced in 1965.

As discussed above, the review of historical aerial photographs and available literature did not reveal evidence for any other landslide events besides the 1965 event. It is considered likely that small landslides (perhaps less than about 20 m^3) could occur more frequently than an event similar in magnitude to the 1965 event. These events could easily go unnoticed (or become forgotten) should they occur in vegetated areas or not result in damage to dwellings.

When more data is available it is common practice to develop landslide size frequency models to present judgments and help predict the future size and frequency of landsliding (e.g. Moon et.al 2005, Hunter et al. 2022). Given that only two landslide-initiating events are known at the site, as well as the uncertainties with rainfall data, we do not believe this approach is practical for this site based on the available data at this time.

B5.2 Empirical landslide runout assessment

B5.2.1 Background

Empirical methods have been used to further compare the landslide runout distances predicted using RAMMS (see Appendix D report) and the observed landslide runouts.

The "fahrböschung" angle (F-angle) assessment is a commonly used, long established rapid screening method for estimating landslide runout. Heim (1932) defined the "fahrböschung" angle as the tangent of the ratio of fall height (H) to horizontal runout distance (L) between the crest of the source zone and toe of the deposit as presented in Figure B26).

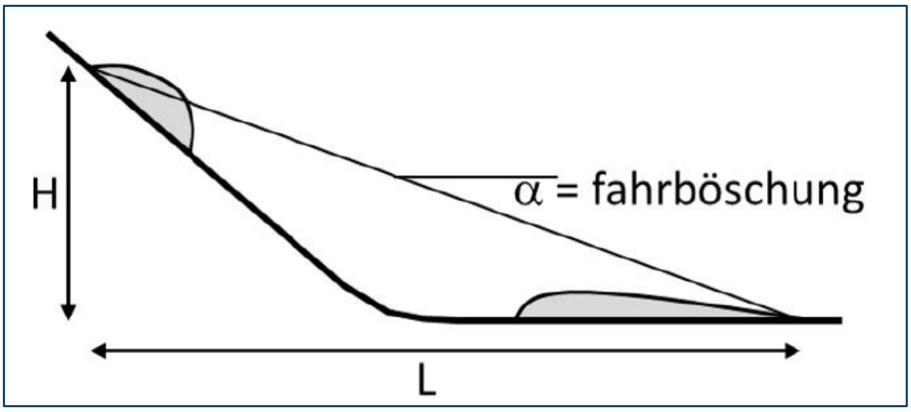


Figure B26 Fahrböschung angle definition after Heim (1932).

Other authors refer to the F-angle by different terms although the definition is the same. For example, Hunter and Fell (2002) adopt the term 'travel distance angle' (referred to by other workers as 'reach angle' or 'angle of reach'). There are many published empirical methods for estimating landslide travel distance (or travel distance angle). Many of these methods are based on slide volume as the main dependent variable (Heim 1932; Scheidegger 1973; Hsu 1975; Smith and Hungr 1992; Corominas 1996; Finlay et al 1999; amongst others). Other authors have proposed empirical expressions based on the inverse relationship between the tangent of the reach angle (H/L) and the landslide volume (i.e. Finlay et al 1999).

Hungr et al. (2005) reported that the volume dependence of the reach has been questioned by several authors for both large landslides (Hsü 1975, Smith and Hungr 1992) and small landslides (Hunter & Fell 2003) and other alternative explanations have been proposed. These works show that there is a lack of agreement among researchers, and opposite conclusions have been derived from these simple relations. Consequently, Hungr et al. (2005) recommends that the use of the F- angle to determine travel distance is made with care.

Finlay et al.'s (1999) data was a mixture of good and modest quality information which is reflected in the large scatter of the predicted travel distances. Hungr et al. (2005) states that Hunter & Fell (2002, 2003) revised this work using more selective good quality data and their recommendations are to be preferred. Hunter & Fell (2002) found that the downslope angle below the source area, provides a useful method for prediction of the travel distance angle for "rapid" slides in natural slopes (Figure B27).

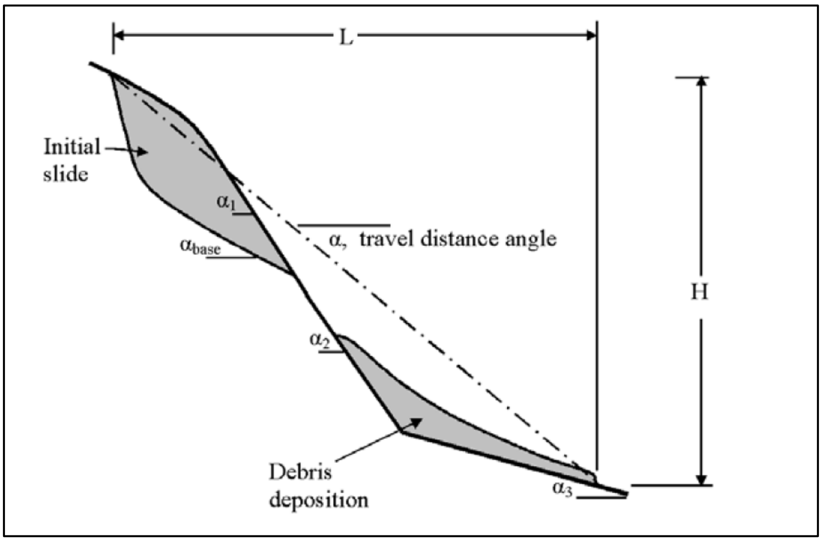


Figure B27 Definition of downslope angle below source area α_2 for slides on steep natural slopes (Hunter & Fell (2002))

B5.2.2 F-angle assessment

Following the February 2023 landslide event AC carried out an area-wide ‘F-angle’ assessment (documented in an internal Auckland Council memo dated 9/03/2023, document ID: AKLCGEO-1790012875-1831). The purpose of this assessment was to inform decision making about managed temporary access (to enable residents to retrieve property, or insurance assessors to assess losses) and amend placard designations. The assessment was not intended for use in long-term decision making or planning.

The AC study used approximately 15 cross sections through landslides to calculate F-angles. The results ranged from 22° to 25°. This range of angles was projected downwards from the crest of the cliff scarps to predict the possible travel distance of future landslides.

As part of this study, GHD carried out an independent F-angle assessment, using new mapping and the LiDAR data captured on 18 February 2023, of 32 landslides located across the escarpment. A summary of the assessment is presented in Table B9. Volumes were estimated from the mapped area of the depletion zone of each landslide, multiplied by the approximated averaged depth; the latter value is given for each landslide in Appendix B-4.

Some of the calculated F-angles should be considered with caution because landslide flows at some locations were affected by built structures such as driveways and houses. Furthermore, in some instances a number of different landslides coalesced and it was not possible to determine where individual landslides stopped.

The assessment revealed a wide range in F-angles ranging from about 16° to 42°. The range is likely attributable to the effects of local topography, degree of channelisation and potentially obstacles such as vegetation and built structures. This review of F-angles at Muriwai suggests that while it is a useful rapid screening method for landslide runout prediction, the range in the data makes it difficult for this method to be used in isolation.

We have also compared the relationship between landslide volume and runout distance by presenting the data on a H / L vs volume plot (Figure B28). As is apparent from the plot, there is a broad scatter of data with a poor correlation between the H / L ratio and landslide volume. Runout estimation methods based on a volume relationship such as Finlay et al (1999) therefore do not appear to be useful in the case of Muriwai. This is consistent with commentary in the literature by Hungr et al. (2005).

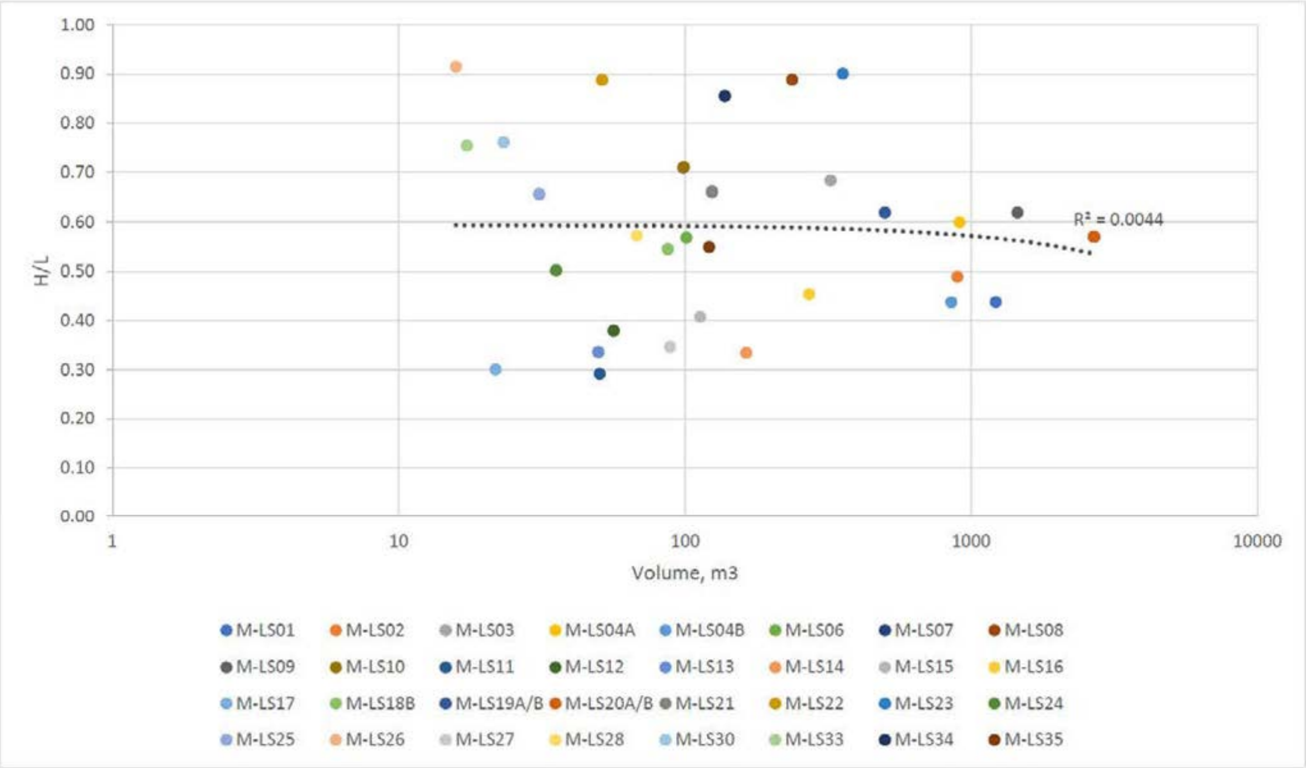


Figure B28 Height / Length ratio vs volume plot for all Muriwai landslides on the main escarpment

B5.2.3 Hunter and Fell (2002) empirical method

Using the Hunter & Fell (2002) method for “rapid” landslides the travel distance angle of the failed slide mass is calculated from assessment of the failure mechanics of the initial slide (whether contractile or dilative on shearing), the type of slope, slide volume, geometry of the slope at and below the slide source area, and the degree of confinement of the travel path of the landslide. Given the predominantly sandy composition of the Muriwai debris flows it is assessed that the material will dilate following the initial failure.

The Muriwai landslide data is presented on a H / L ratio vs tangent of the downslope angle plot according to the Hunter & Fell (2002) method (Figure B29). This also includes data for the 1965 landslide. Regression lines have also been established based on the degree of confinement. The regression line for a ‘partially confined’ travel path was found to be very similar to the Hunter & Fell (2002) regression line for a ‘partially confined’ travel path.

Table B10 presents the predicted travel distance angles for a range of slope angles using this method.

Comparison of the method with the known F-angles calculated for several of the February 2023 Muriwai landslides typically found agreement within a few degrees.

The predicted travel distances using the Muriwai relationship are very similar to the Hunter & Fell (2002) method, albeit usually at the higher end of the travel distance angle range. Based on the results of this exercise there is a good correlation between landslide runout and the downslope angle for the landsliding at Muriwai, meaning that landslide runout will vary across the escarpment depending on the local geomorphology. The close similarity between the Hunter & Fell (2002) predictive method and the Muriwai relationship probably suggests that while some variability is to be expected, future landslides are unlikely to travel appreciably further than the observed February 2023 runout distances.

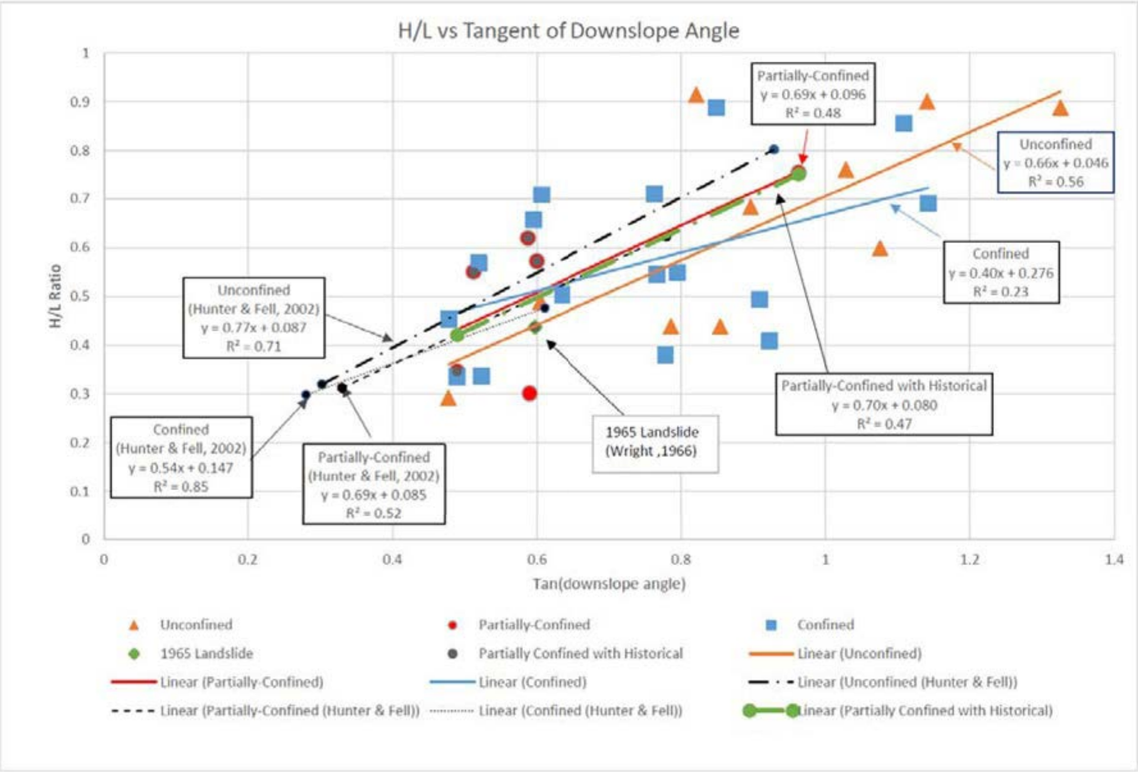


Figure B29 *H/L versus tangent of the downslope angle α_2 plot for Muriwai data together with Hunter & Fell (2002) relationships for rapid slides on steep natural slopes in dilative soils.*

Table B9 Summary of F-angle assessment

Landslide ID	Length (m)	Height (m)	Downslope Angle (α_2)	F-Angle	Estimated Landslide volume (m^3)	Comments
M-LS01	142.8	62.6	38	24	1222	
M-LS02	133.6	65.396	31	26	899	
M-LS03	89.1	60.9	42	34	324	
M-LS04A	108	64.7	47	31	914	
M-LS04B	147.8	64.7	41	24	855	Length measured from landslide centreline due to channelised landslide flow
M-LS06	113.4	64.4	27	30	101	
M-LS07	59.5	42.2	31	35	99	Difficult to determine toe of slide due to coalescence of adjacent debris flows
M-LS08	69.2	61.5	40	42	237	Difficult to determine toe of slide due to coalescence of adjacent debris flows
M-LS09	131.4	81.4	30	32	1457	
M-LS10	88.7	63	37	35	99	
M-LS11	44.2	12.9	25	16	50	Slide originated on lower escarpment slope. Length measured from landslide centreline due to channelised landslide flow
M-LS12	84.3	32.02	38	21	56	
M-LS13	57.7	19.4	28	19	50	Flow appears to have been channelised along driveway - runout may be misleading
M-LS14	66.4	22.2	26	18	164	Length measured from landslide centreline due to channelised landslide flow
M-LS15	48.1	19.6	43	22	113	
M-LS16	44.3	20.1	26	24	272	
M-LS17	23.6	7.1	31	17	22	Small, localised landslide on lower escarpment slope
M-LS18B	131.7	71.7	37	29	87	Length measured from landslide centreline due to channelised landslide flow
M-LS19B	116	63.8	27	29	500	
M-LS20B	139.1	68.6	42	26	2692	
M-LS21	57.3	39.6	49	35	124	

Landslide ID	Length (m)	Height (m)	Downslope Angle (α_2)	F-Angle	Estimated Landslide volume (m^3)	Comments
M-LS22	17.9	15.9	53	42	51	
M-LS23	30.3	27.3	49	42	357	
M-LS24	39.2	19.7	32	27	35	
M-LS25	41.6	27.3	31	33	31	
M-LS26	9.4	8.6	39	42	16	Small, localised landslide on lower escarpment slope
M-LS27	35.8	12.4	26	19	89	Small, localised landslide originating on ridgeline - lower escarpment slope
M-LS28	20.8	11.9	31	30	68	
M-LS30	13.4	10.2	46	37	23	
M-LS33	26.9	20.3	44	37	17	Small, localised landslide on lower escarpment slope
M-LS34	63.7	54.5	48	41	138	Difficult to determine toe of slide due to coalescence of adjacent debris flows
M-LS35	81.8	44.9	39	29	122	

Table B10 Summary of predicted travel distance angles

Downslope Angle (°)	Predicted Travel Distance Angle (°) (Hunter and Fell (2002) empirical method)*	Predicted Travel Distance Angle (°) – Muriwai Regression Data
20	19	19
25	22	23
30	25 - 26	26
35	28 - 30	30
40	31 - 34	34
45	34 - 38	38
50	38 - 42	43
55	43 - 47	47
60	47 - 52	52

*Confined and partly confined travel pat

B6. Landslide hazard assessment

B6.1 Inferred future landslide source areas

The distribution of potential landslides is an important consideration for the assessment of future debris flow risks (see Appendix D for rationale and reference to figures that show inferred potential landslide sources). Appendix E quantifies the relative risk of damaging landslides for each zone.

Potential landslide failure zones have been identified based on having similar geomorphology (ground shape) and geology to February 2023 landslide source areas. For example, the bowl-shaped head-scarp shape of recent landslides observed at the crest of the escarpment is similar to the shape of the escarpment where failures did not occur in 2023 (Figure B30) but have almost certainly occurred at some time in the past. Hence, we infer that the whole of the escarpment has similar landslide susceptibility due to the likely similar conditions of geology and possibly groundwater. We have assumed that future landslides on the escarpment have the potential to fail with similar damaging effects as the February 2023 landslides. Inferred landslides were used as RAMMS debris flow source areas to model potential future landslide hazard areas (see the Appendix D RAMMS analysis report).

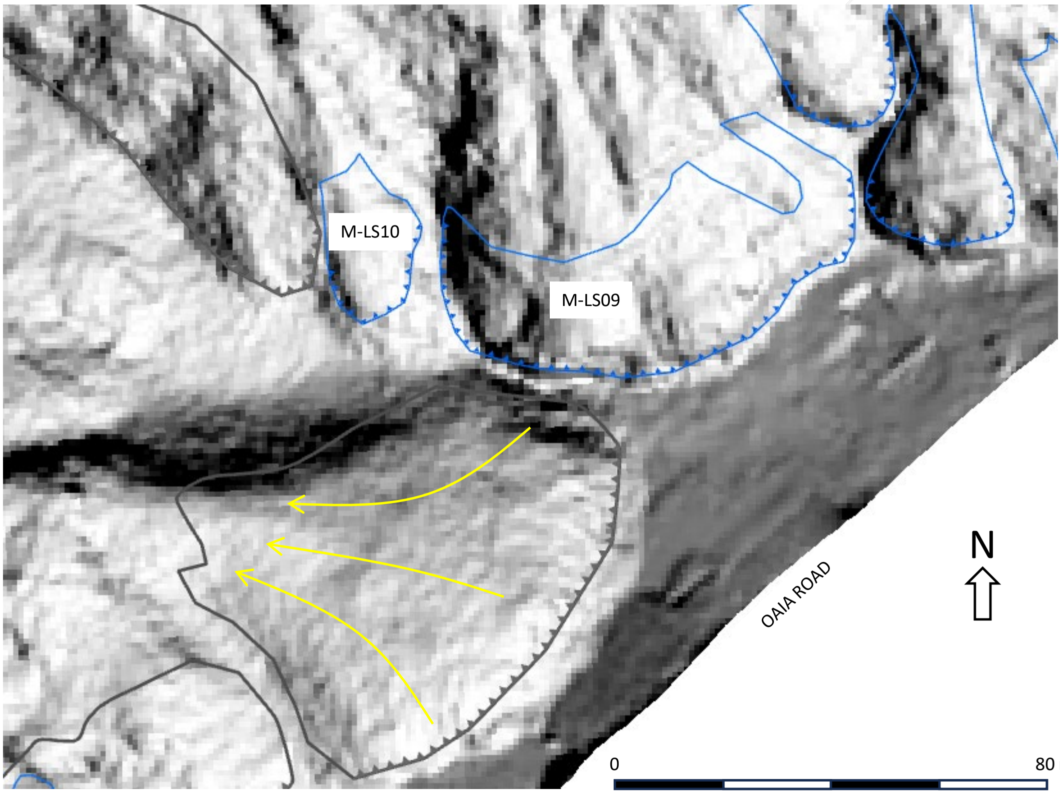


Figure B30 ***Potential landslide failure zones have been identified by GHD based on having similar geomorphology (ground shape) and geology to February 2023 landslide source areas. The above example shows a potential landslide source zone (grey outline) that has similar bowl-shaped characteristics to recently failed blue areas. Yellow lines indicate expected debris flow path. Background surface model has a 'hill shade' applied to highlight the geomorphology. Location is below the escarpment and west of Oaia Road.***

B6.2 Potential for deep-seated landslides within Awhitu Formation

Two instances of deep-seated landslide activity are observed or inferred within Awhitu Formation sand surrounding the study area. These features are located outside of and within the study area, respectively. The mode and cause of failure are not considered to be related to the trigger event associated with the 2023 landslides resulting from Cyclone Gabrielle.

- A deep-seated translational landslide is present within the Awhitu Formation, south of the study area, immediately south of Waitea Road (Figure B31). Its geomorphology is suggestive of an earth flow. The toe region of the landslide appears to be un-buttressed and eroding into the ocean over a large cliff line. The outcropping Nihotupu Formation at the toe of the slope is inferred to control the depth of slip by acting as a relatively impermeable barrier to groundwater flow. This underlying unconformity is the same feature interpreted to dip below the study site from the southern end of Domain Crescent (Section B4.5).
- The possibility for a large, 'ancient' landslide identified from surface geomorphology and subsurface core recovered in BH-M06 was raised in Section B4.5 and. A feature of this scale would likely be complex in its mode and mechanism of failure and, as implied from BH-M06, the principal slip surface may extend several tens of meters below ground.

These modes of landslide failure are not considered applicable to the study area and the debris flow hazard off the escarpment at Muriwai township.

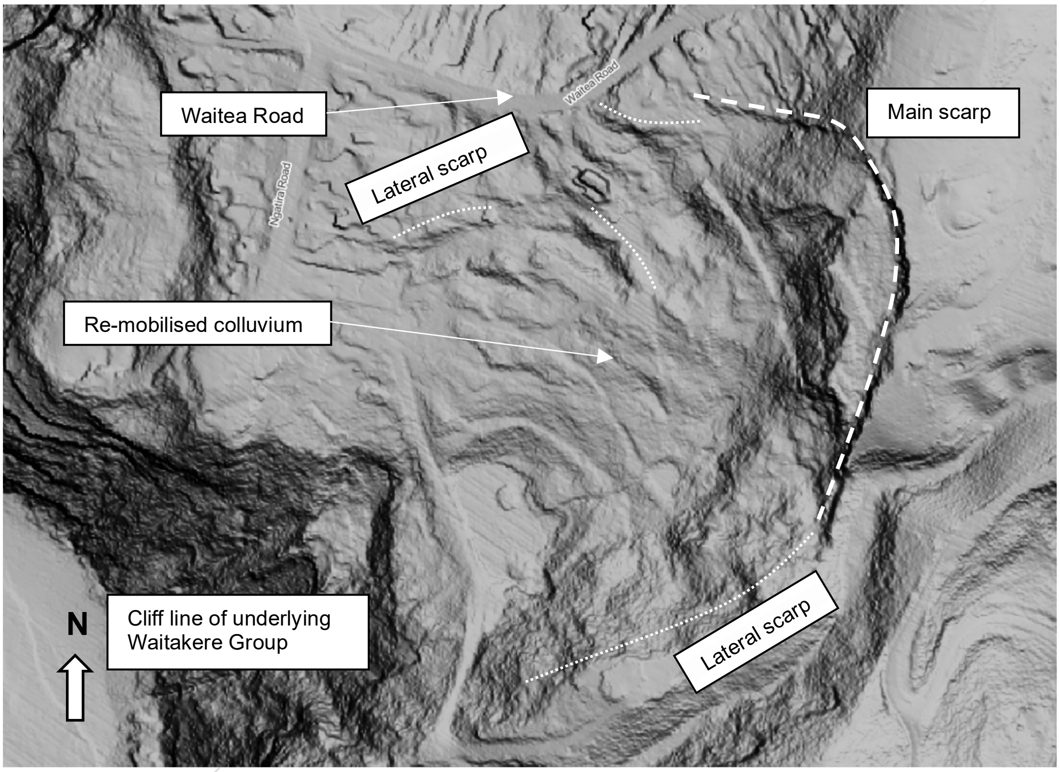


Figure B31 Deep seated landslide (earthflow) within Awhitu Sand Formation, underlying contact with Waitakere Formation daylighting in toe area (cliffs). Background surface model has a 'hill shade' applied to highlight the geomorphology.

B6.3 Geomorphological landslide zones

B6.3.1 Definition and overview of zones

The study area has been divided into six geomorphological 'zones' based on the surface topography, February 2023 landslide characteristics and general geomorphology. The purpose of this is to differentiate areas according to their susceptibility to large-scale[3] landslides. The life risk to residents for each zone is considered separately in the risk assessment (see overall report Appendix E).

To help define the zones, we applied a colour scale to a plan of Muriwai (Figure A125 in Appendix A) to highlight the topographic variation and show areas that are steeper than others. Cross sections were then used to generate slope profiles, mostly normal to the Muriwai escarpment, but in some cases below the escarpment, and the profiles were overlain to identify similarities and differences.

---

[3] In this report 'large scale' landslide hazards refers to landslides originating from the main escarpment that typically have a volume of more than about 50 m^3 with the potential to cause total or partial collapse of a dwelling.

The slope angle and approximate height of the steeper section of the profile is shown for each zone in Table B11. This estimate is subjective and is an approximation only, however, it is a sound basis for differentiating between zones.

Table B11 Summary of slope angle and height for zone profiles (zones coloured to match profile colours)

Zone	Average Angle	Minimum Angle	Maximum Angle	Approximate vertical height to nearest 10 m
1	30	26	31	20
2	33	30	41	70
3	25	23	30	60
4	44	NOT APPLICABLE DUE TO VARIABLE SLOPE PROFILE SHAPES	50	
5	38		30	
6	39		20	

Figure B32 shows the slope profiles, coloured according to zone to allow comparison. The common point of reference for the profiles is the top of the slope (i.e. the top of the escarpment).

Similarly, comparison of the number of landslides and the distribution of these according to zone highlights the spatial variability of these (see Figure B33 and Figure B34).

The following sections describe the landslide and topographic characteristics of each zone referring to these data.

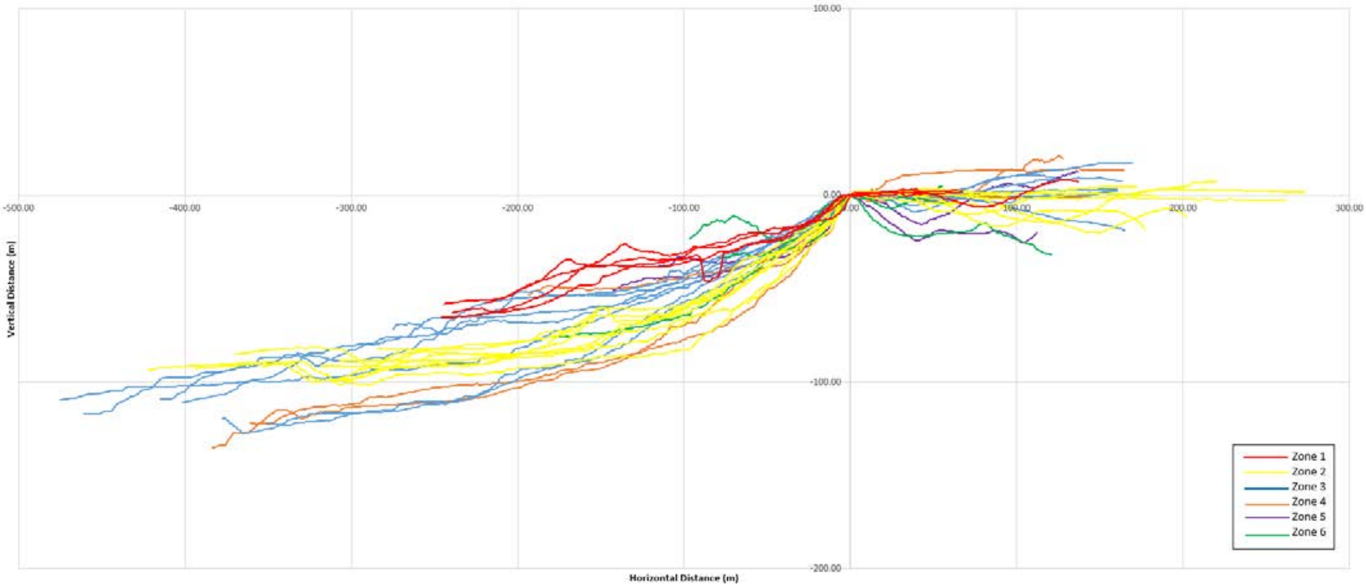


Figure B32 Slope profile comparison of 27 cross sections in Zones 1 to 6 (see Figure A137). Profiles are mostly viewed in a north-looking direction and have been centred on the crest of each slope (in most cases this is the top of the escarpment).

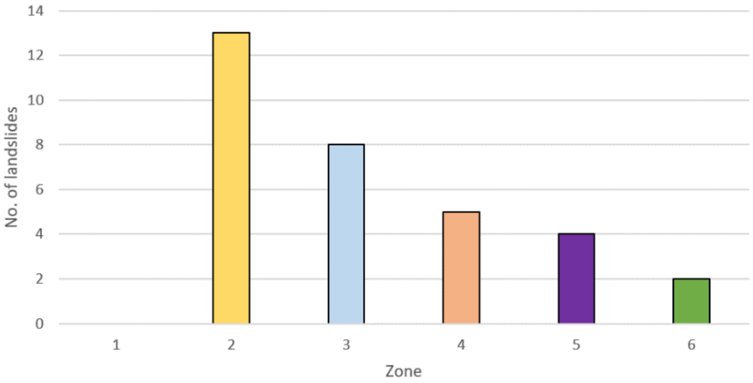


Figure B33 Number of February 2023 landslides per zone

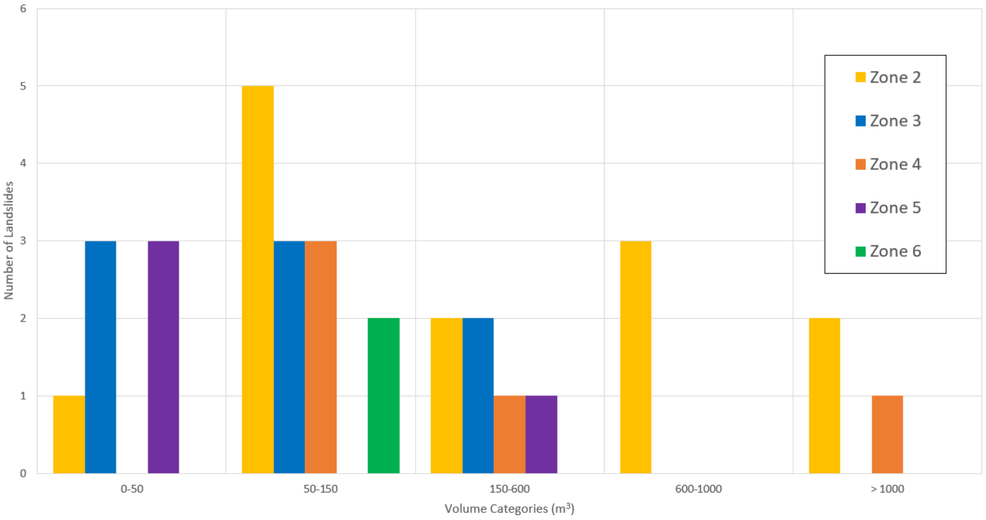


Figure B34 Number and size of February 2023 landslides shown per zone

B6.3.2 Zone characterisation

6.3.2.1 Zone 1

Zone 1 is located at the northern end of Motutara Road north of, and including, 42 and 104 Motutara Road (see Figure B35). The features of Zone 1 are as follows:

- The steepest part of the slope at the top of Motutara Road is approximately 30°, which is relatively flat (see Figure B36).
- The vertical height of the slope at this steepness is approximately 20 m, which is one of the lowest on the escarpment.
- No large landslides occurred in this area in the February 2023 storm event.
- The general slope-facing direction is towards the southwest, which may not directly face the direction of origin for sub-tropical cyclone storm events.

When considering the potential for future landslides, we have considered that Zone 1 may have favourable conditions (low susceptibility) partly due to the location of Motutara Road at the upper part of the slope (i.e. in the vicinity of 42 Motutara Road), which may act to intercept and redirect surface flows from further up the slope, and partly due to its aspect. In addition, anecdotal evidence from community interaction is that the surface water conditions during the February 2023 storm were not notably extreme, with no observed concentrated flow.

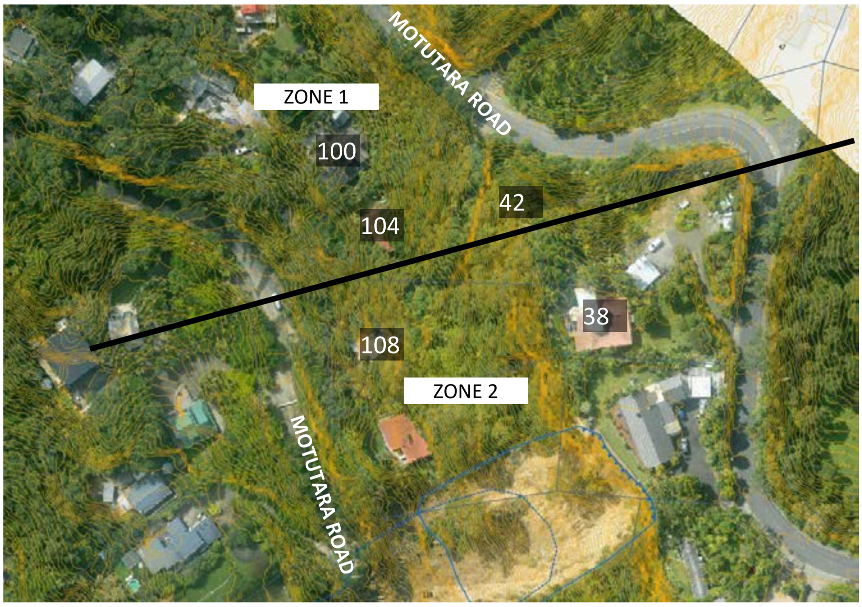


Figure B35   ***Location of the Zone 1 / Zone 2 boundary. North is to the top of the page.***

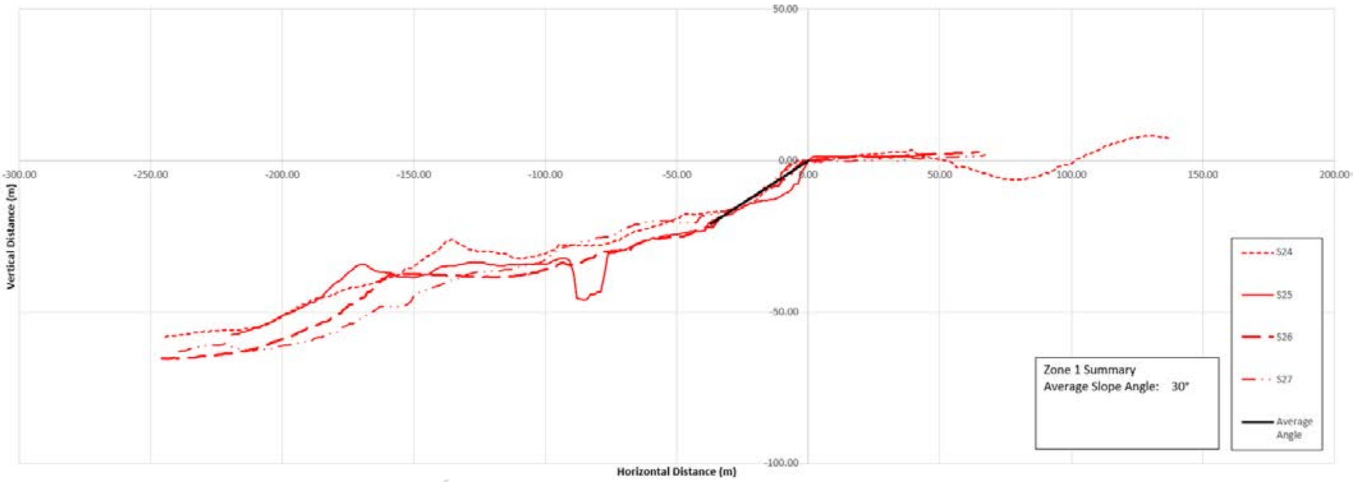


Figure B36   ***Slope profile comparison of Zone 1 surface cross sections (see Figure A137 for location of sections)***

6.3.2.2 Zone 2

Zone 2 is the largest zone and is above Motutara Road. It is defined in the north by, and including, 38 and 108 Motutara Road (see Figure B35) while the southern limit of Zone 2 is bounded by, and includes, 228 and 230 Motutara Road (see Figure B43). The features of Zone 2 are as follows:

- The average slope angle is 33° but is locally much steeper (see Figure B37).
- The vertical height of the slope is greater than 70 m on average, which is the highest of all zones.
- Thirteen large landslides occurred in Zone 2 in the February 2023 storm, with two having a volume greater than 500 m^3. The landslides are commonly broader relative to other zones (e.g. Zone 3).
- The general slope-facing direction is to the west, which is expected to be towards future sub-tropical cyclone storm events.
- The shape of the escarpment tends to be mostly gently and continuously curving. Elsewhere on the escarpment, for example in Zone 3, there are many distinctive, tightly curved headscarp features.

The above observations align well with this area having the potential for multiple, highly damaging landslides, as was the case in the February 2023 event.

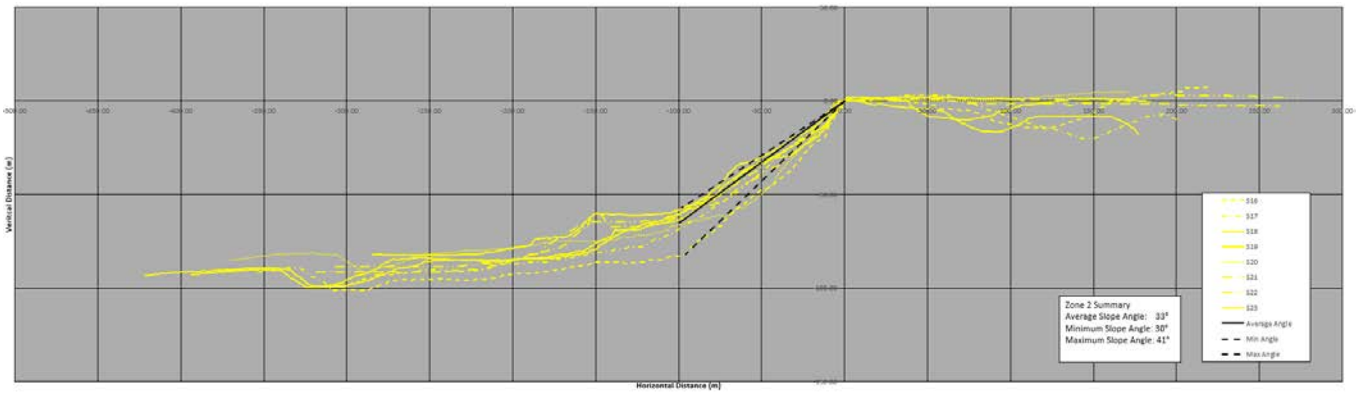


Figure B37 *Slope profile comparison of Zone 2 surface cross sections (see Figure A137 for location of sections)*

6.3.2.3 Zone 3

Zone 3 is located at the Muriwai escarpment above Domain Crescent, being defined to the north by properties on the northern side of Domain Crescent (see Figure B43) and to the south by 63 Domain Crescent (see Figure B38). The features of Zone 3 are as follows:

- The slope is approximately 25° on average, which is relatively flat (see Figure B39).
- The vertical height of the slope at this steepness is approximately 60 m, which is relatively high.
- Eight large landslides occurred in February 2023, all with a volume of less than 600 m^3.
- The general slope-facing direction is to the west, which is potentially towards future sub-tropical cyclone storm events.
- The escarpment has many distinctive, tightly curved headscarps in marked contrast with Zone 2. Debris flows are typically more channelised in this zone.

The observations above indicate a regime with potential for large, destructive landslides.

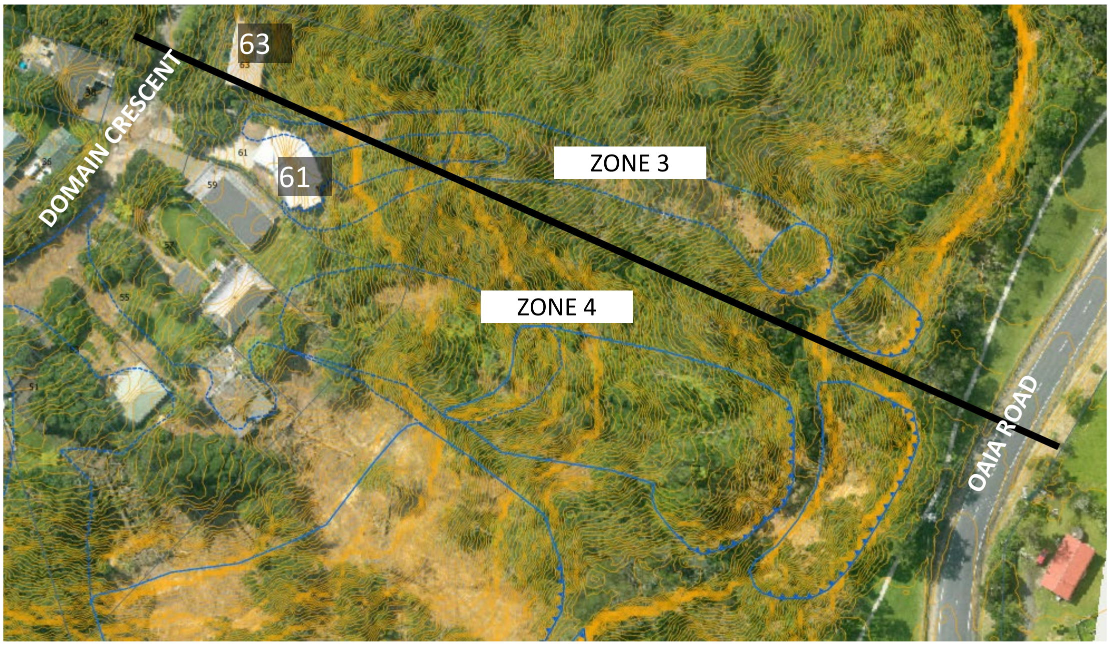


Figure B38 *Location of the Zone 3 / Zone 4 boundary. North is to the top of the page.*

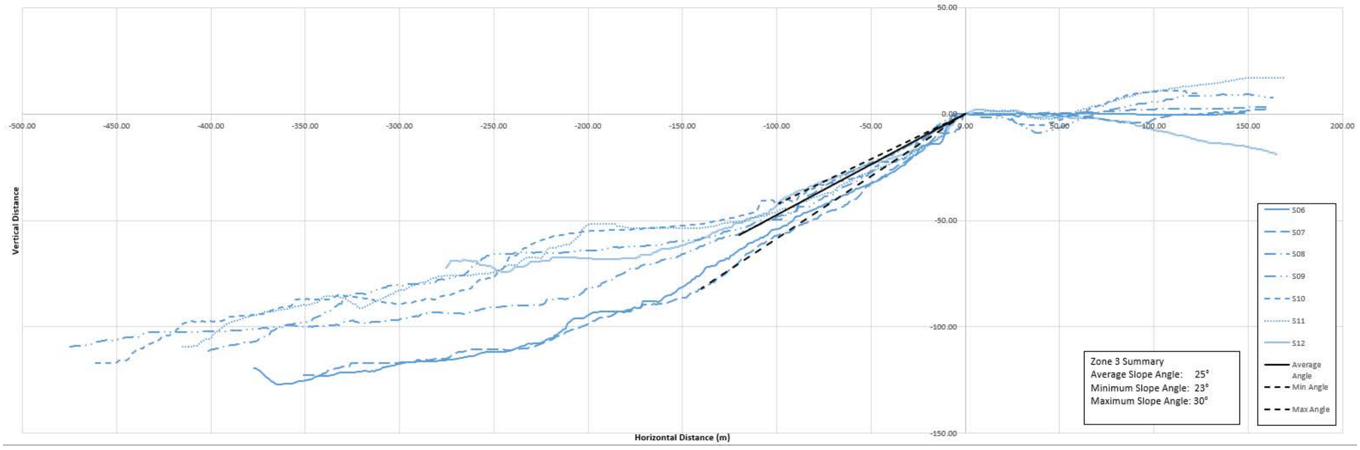


Figure B39 Slope profile comparison of Zone 3 surface cross sections (see Figure A137 for location of sections)

6.3.2.4 Zone 4

Zone 4 is located at the southern end of Domain Crescent between 47 and 61 Domain Crescent (see Figure B40 and Figure B38, respectively). The features of Zone 4 are as follows:

- The average slope angle is 44°, which is relatively steep (see Figure B41).
- The vertical height of the slope at this steepness is approximately 50 m, which is less than in Zones 2 and 3.
- Five large landslides occurred in February 2023, with one over 1000 m^3 in volume. Note that Zone 4 is smaller than other, similar zones and so the number of landslides may give a false impression of the exposure of dwellings at the slope base.
- This is the location of the large 1965 landslide (see Section B3.3.2).
- The general slope-facing direction is to the west, which is expected to be towards future sub-tropical cyclone storm events.
- The escarpment has many distinctive, tightly curved headscarps.

The observations above indicate a regime with a demonstrated potential for large, destructive landslides on a similar scale to Zone 2.

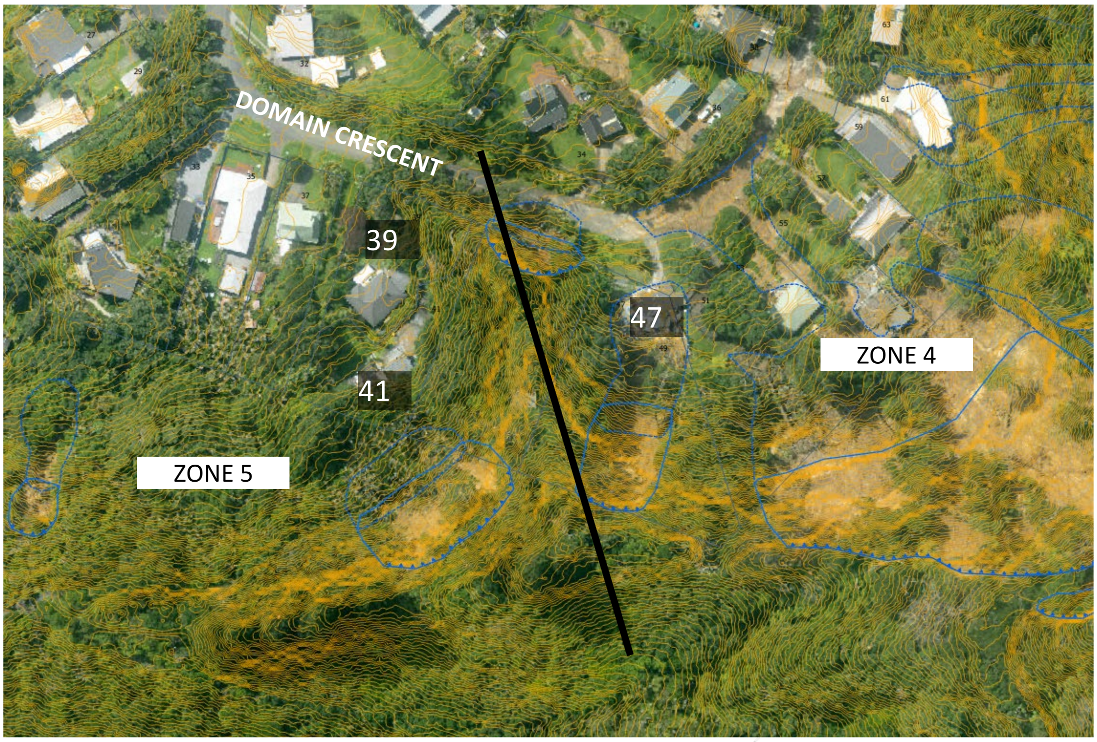


Figure B40 Location of the Zone 4 / Zone 5 boundary. North is to the top of the page.

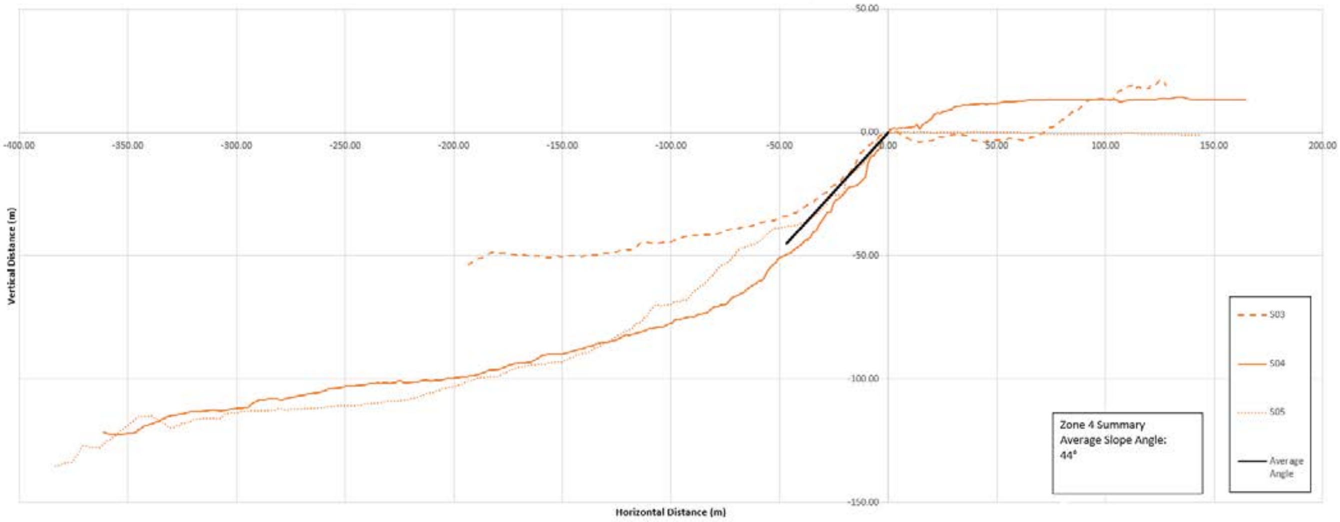


Figure B41 Slope profile comparison of Zone 4 surface cross sections (see Figure A137 for location of sections)

6.3.2.5 Zone 5

Zone 5 is the southernmost zone between Domain Crescent and Waitea Road. The boundary of Zone 5 is to the east of 39 and 41 Domain Crescent (see Figure B40). The features of Zone 5 are as follows:

- The slope is approximately 38°, which is derived from only two cross sections (see Figure B42).
- The slope facing Domain Crescent is one side of a ridge, meaning that the catchment for surface water or groundwater recharge is limited compared with escarpment zones. This may mean that Zone 5 is less susceptible to landslides.
- Four landslides occurred in the February 2023 storm, most of which were less than 50 m^3; none impacted dwellings.
- The general slope-facing direction is towards the northwest, which may be the direction of origin for future sub-tropical cyclone storm events.

When considering the potential for future landslides, we suggest that Zone 5 may have favourable conditions due to the topography, which does not encourage storage of groundwater behind the slope, and the limited potential for surface runoff to saturate the slope.

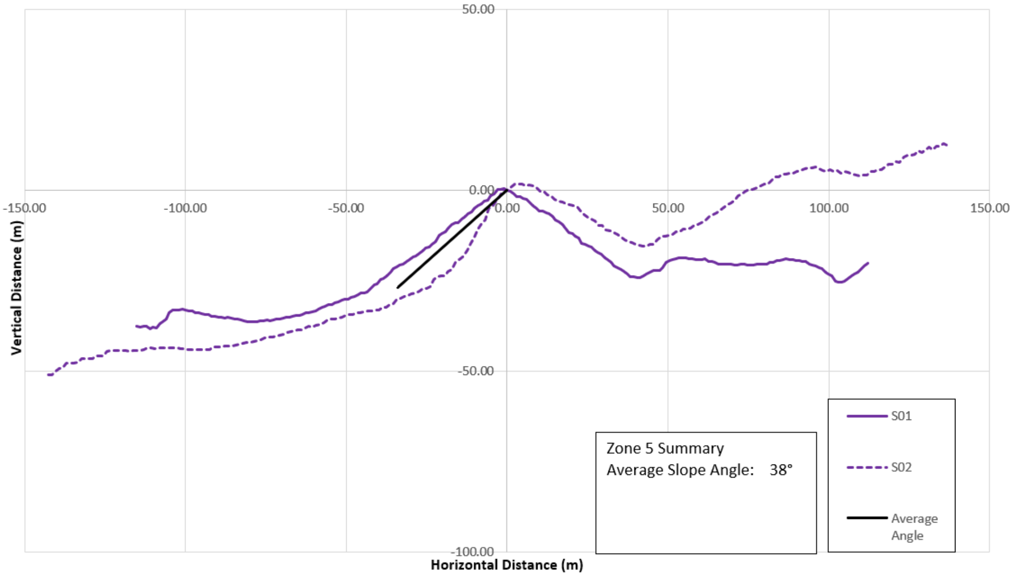


Figure B42 *Slope profile comparison of Zone 5 surface cross sections (see Figure A137 for location of sections)*

6.3.2.6 Zone 6

Zone 6 is located between Zone 3 and 2. It includes 264 Motutara Road to the west through to 232 Motutara Road to the east (see Figure B43). This zone is away from the Muriwai escarpment but is locally steeper than surrounding land. The features of Zone 6 are as follows:

- The average steepness of the three cut profiles is about 39°, although the variability of the profiles is noted (see Figure B44).
- The vertical height is approximately 20 m, which is relatively low.
- Two landslides in the range of 50 to 150 m^3 were recorded following the February 2023 storm event.
- The general slope-facing direction is towards the north.

When considering the potential for future landslides, we consider that Zone 6 may have favourable conditions due to the topography, which does not encourage storage of groundwater behind the slope, the low slope height, and limited potential for surface runoff/saturation.

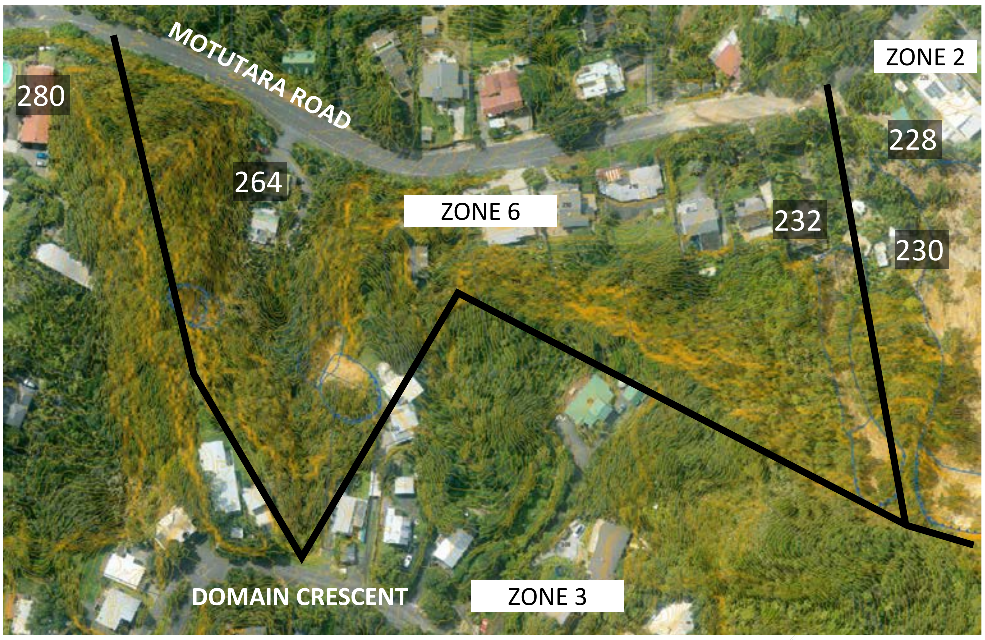


Figure B43 Location of the Zone 2 / Zone 3 / Zone 6 boundary. North is to the top of the page.

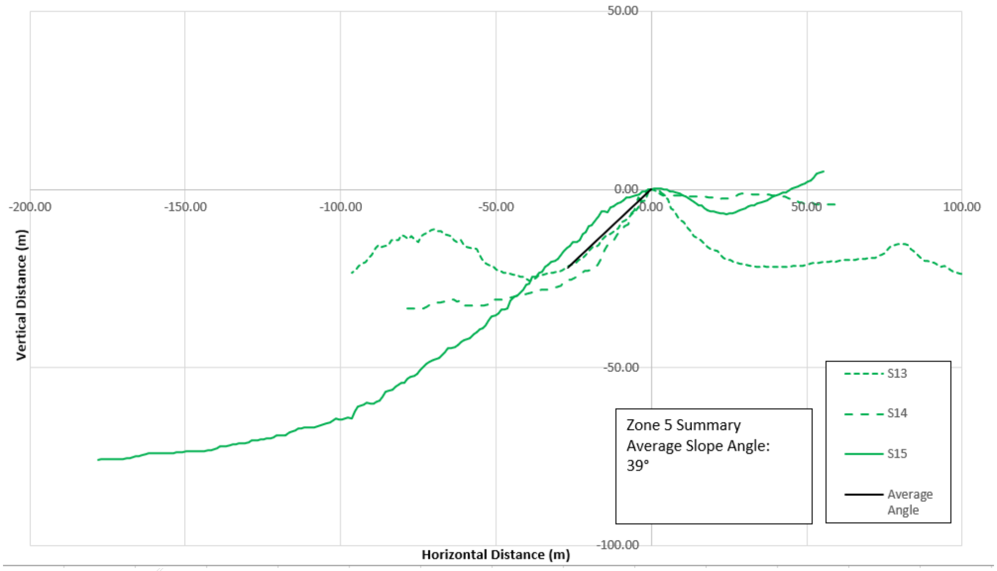


Figure B44 Slope profile comparison of Zone 6 surface cross sections (see Figure A125 for location of sections)

B7. Conclusions

The following conclusions are made in relation to the engineering geological assessment of the Muriwai landslide hazard:

1. The recent (2023) and historical (1965) landslides that have affected the Muriwai community were high-velocity debris flows originating on the escarpment that extends up to 80 m above the township.
2. The model proposed for the recent (2023) and historical (1965) landslides that damaged the Muriwai community is that of saturated and shallow translational slips that quickly become high-velocity debris flows, entraining significant volumes of unconsolidated sand and vegetation.
3. The formation of these landslides can be directly attributed to the saturation of surficial soil (colluvium and weathered rock) in the Awhitu Sand Formation which, upon losing its binding iron-cement, develops a shallow shear surface.
4. This process is probably influenced by a combination of surface water infiltration and subsurface pore pressure increases from perched aquifers and associated springs. However, as no groundwater or overland flow data is available from during the events, reliance is placed on anecdotal accounts which do not provide a clear picture.
5. From the data available, including continuous groundwater monitoring established after the 2023 event, it is inferred that surface water flow and infiltration/saturation of shallow soils has had the greater effect on the onset of landslides.
6. The speed, composition, and volume of the debris generated make these debris flows highly destructive to dwellings and property located within the run-out area. As a result, tragically, multiple fatalities were experienced in both the 1965 and 2023 events.
7. The debris flows follow local catchment valleys which often coalesce multiple landslides into confined areas. Consequently, the location and degree of damage to residential properties is variable along Domain Crescent and Motutara Road.
8. Deep-seated landslides resulting from large (i.e. ARI 100 year) rain events within the study area (escarpment) and geology (Awhitu Formation) sand, are not considered likely. Although evidence that may be plausibly attributed to larger historical landslides has been observed, the relative magnitude of these features compared with the 2023 event suggests much larger, less frequent environmental conditions would be required to instigate failure (most likely a very large earthquake). Such conditions and resultant hazards have not been considered for this assessment.
9. Six geomorphological landslide ‘zones’ have been defined based on the surface topography, 2023 landslide characteristics and general geomorphology of the study area. These differentiate areas according to their susceptibility to large-scale landslides (i.e. having a volume of more than approximately 50 m^3). Zones 2, 3 and 4 contain the Muriwai escarpment and have higher potential for future, large landslides.
10. The life risk to residents for each zone is considered separately in the risk assessment (Appendix E).

B8. Limitations

This report has been prepared by GHD Limited (GHD) for Auckland Council and may only be used and relied on by Auckland Council for the purpose agreed between GHD and Auckland Council as set out in Section 1 of this report.

GHD otherwise disclaims responsibility to any person other than Auckland Council arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions and conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

The opinions, conclusions and any recommendations in this report are based on information obtained from, and testing undertaken at or in connection with, specific sample points. Site and ground conditions inferred at other parts of the site may be different from the site conditions found at the specific sample points.

The opinions, conclusions and any recommendations in this report are based on assumptions made by GHD described in this report (refer Section 1 of this report). GHD disclaims liability arising from any of the assumptions being incorrect.

GHD does not accept responsibility arising from, or in connection with, varied conditions and any change in conditions. GHD is also not responsible for updating this report if the conditions change.

An understanding of the geotechnical site conditions depends on the integration of many pieces of information, some regional, some site specific, some structure specific and some experienced based. Hence this report should not be altered, amended, abbreviated, or issued in part in any way without prior written approval by GHD. GHD does not accept liability in connection with the issuing of an unapproved or modified version of this report.

Verification of the geotechnical assumptions and/or model is an integral part of the design process - investigation, construction verification, and performance monitoring. If the revealed ground or groundwater conditions vary from those assumed or described in this report the matter should be referred back to GHD.

B9. References

Technical Literature

Auckland Council (2023). 'Guidelines on the use of AGS (2007) for landslide risk assessment in Auckland following the 2023 flooding and cyclone'. Memorandum dated 20 September 2023.

B. W Hayward (1976): 'Lower Miocene geology and sedimentary history of the Muriwai-Te Waharoa coastline, North Auckland, New Zealand'; New Zealand Journal of Geology and Geophysics, Volume 19, No. 5

B. W Hayward (1979): 'Ancient Undersea Volcanoes: A guide to the geological formations at Muriwai, west Auckland"; Geological Society of New Zealand Guidebook No. 3'

B. W Hayward (2022). The tragic 1965 Muriwai Landslide. Geocene 28: 2-5

Corominas, J. (1996). The angle of reach as a mobility index for small and large landslides. Canadian Geotechnical Journal, Vol 33, pp. 260-271.

D. J.: 'Slope movement types and processes. In Special Report 176: Landslides: Analysis and . Varnes, 1978Control'; TRB National Research Council Washington.

D.M. Cruden & D. J. Varnes (1996): 'Landslide Types and Processes'; Transportation Research Board, U.S. National Academy of Sciences, Special Report, 247: 36-75

Fell R., Ho K.K.S., Lacasse S., Leroi E. (2005). A framework for landslide risk assessment and management. In: Hungr O, Fell R, Couture R, Eberhardt E (eds) Landslide risk management. Taylor & Francis, London, pp 533–541

Finlay P.J.; Mostyn G.R. and Fell R. (1999). Landslides: Prediction of travel distance and guidelines for vulnerability of persons. Proceedings of the 8th Australia New Zealand Conference on Geomechanics, (Vitharana and Colman eds.) Hobart, Australian Geomechanics Society, pp. 105-113.

GHD (2023^1). Muriwai Resilience Assessment – Stormwater; Private Property Desktop Assessment Report. For Auckland Council. 15 December 2023.

GHD (2023^2). Muriwai Resilience Assessment – Stormwater; Oaia Road and Edwin Mitchelson Track Investigation Report. For Auckland Council. 18 December 2023.

Heim, A. (1932). Landslides and human lives (Bergstruz and Menchen leben). Translated by N. Skermer. BiTech Publishers, Vancouver, B.C., 195 p

Hsu, K.J. (1975). Catastrophic debris streams (sturzstroms) generated by rockfalls. Geological Society of America Bulletin, Vol 86, pp. 129-140.

Hungr, O., Leroueil, S. and Picarelli, L. (2014). The Varnes Classification of Landslide Types, an Update. Landslides (2014) 11:167–194

Hungr. O.; Corominas, J. and Eberhardt, E. (2005). Estimating landslide motion mechanisms, travel distance and velocity. In Landslide Risk Management Editors. O. Hungr, R. Fell, R. Couture and E. Eberhardt. Taylor and Francis, London. 99-128.

Hunter, G. & Fell, R. (2003). Travel distance angle for rapid landslides in constructed and natural soil slopes. Canadian Geotechnical Journal 40(6): 1123-1141.

Hunter. A., Flentje, F. and Moon. A. (2022). Bulli Pass Landslide Risk Management Part 1. Australian Geomechanics, Vol 57, No3.

Hunter. G., & Fell. R. (2002). Estimation of Travel Distance for Landslides in Soil Slopes. Australian Geomechanics, Vol 37, No2.

J. C. Schofield, 1975: 'Sea-level fluctuations cause periodic, post-glacial progradation, South Kaipara Barrier, North Island, New Zealand'; New Zealand Journal of Geology and Geophysics, Volume 18, No. 2

L. W. Wright, 1966: 'The Muriwai Debris-Avalanche: Some Aspects of Its form and Genesis'; New Zealand Geographer

Moon A.T., Wilson R.A. and Flentje P.N. (2005). Developing and using landslide size frequency models. In: Hungr O, Fell R, Couture R and Eberhardt, E (eds) Landslide Risk Management, CRC Press, pp 681-690.

P.R. Goldsmith & E.H Smith, 1984: “Tunnelling soils in South Auckland, New Zealand”; Fourth Australia – New Zealand Conference on geomechanics, Perth, 14-18 May 1984

Rodney District Council, 2005: “Muriwai Community Plan”; Strategy and Policy

Scheidegger, A.E. (1973) On the prediction of the reach and velocity of catastrophic landslides. Rock Mechanics, Vol 5, pp. 231-236.

Smith, D. and Hungr, O. (1992) Failure behaviour of large rockslides – Report to the Geological Survey of Canada and BC Hydro and Power Authority. Report No. 16-11-6, Thurber Engineering Ltd.

Public Articles

Interest New Zealand. Brooke, 21 Feb 2023, from Learning the lessons from landslides | interest.co.nz

Paper Past New Zealand. 1965. Papers Past | Newspapers | Press | 2 September 1965 | Mopping Up After Slips (natlib.govt.nz) PRESS, VOLUME CIV, ISSUE 30845, 2 SEPTEMBER 1965, PAGE 3

Stuff New Zealand. 15 Aug 2013, from Old memories revisited | Stuff.co.nz

Auckland Star. 20 June 1934. Papers Past | Newspapers | Auckland Star | 20 June 1934 | THE DELUGE. (natlib.govt.nz) AUCKLAND STAR, VOLUME LXV, ISSUE 144, 20 JUNE 1934, PAGE 9

Manawatu Standard. 27 Dec 1926. Papers Past | Newspapers | Manawatu Standard | 27 December 1926 | FLOODS IN THE NORTH. (natlib.govt.nz) MANAWATU STANDARD, VOLUME XLVII, ISSUE 24, 27 DECEMBER 1926, PAGE 8

Evening Star. 27 Dec 1926. Papers Past | Newspapers | Evening Star | 27 December 1926 | RECORD FLOOD (natlib.govt.nz) EVENING STAR, ISSUE 19441, 27 DECEMBER 1926, PAGE 7

Wairarapa Daily Times. 1926. Papers Past | Newspapers | Wairarapa Daily Times | 28 December 1926 | UNSEASONABLE WEATHER. (natlib.govt.nz) WAIRARAPA DAILY TIMES, 28 DECEMBER 1926, PAGE 5

Southland Times. 28 Dec 1926. Papers Past | Newspapers | Southland Times | 28 December 1926 | AUCKLAND’S RAIN (natlib.govt.nz) SOUTHLAND TIMES, ISSUE 20063, 28 DECEMBER 1926, PAGE 7

Christchurch Star. 27 Dec 1926. Papers Past | Newspapers | Star (Christchurch) | 27 December 1926 | The Worst Floods For Fifty Years Do Damage In... (natlib.govt.nz) STAR (CHRISTCHURCH), ISSUE 18039, 27 DECEMBER 1926, PAGE 7

Evening Post, 28 Dec 1922. Papers Past | Newspapers | Evening Post | 28 December 1922 | HEAVY FLOODS (natlib.govt.nz) EVENING POST, VOLUME CIV, ISSUE 154, 28 DECEMBER 1922, PAGE 7

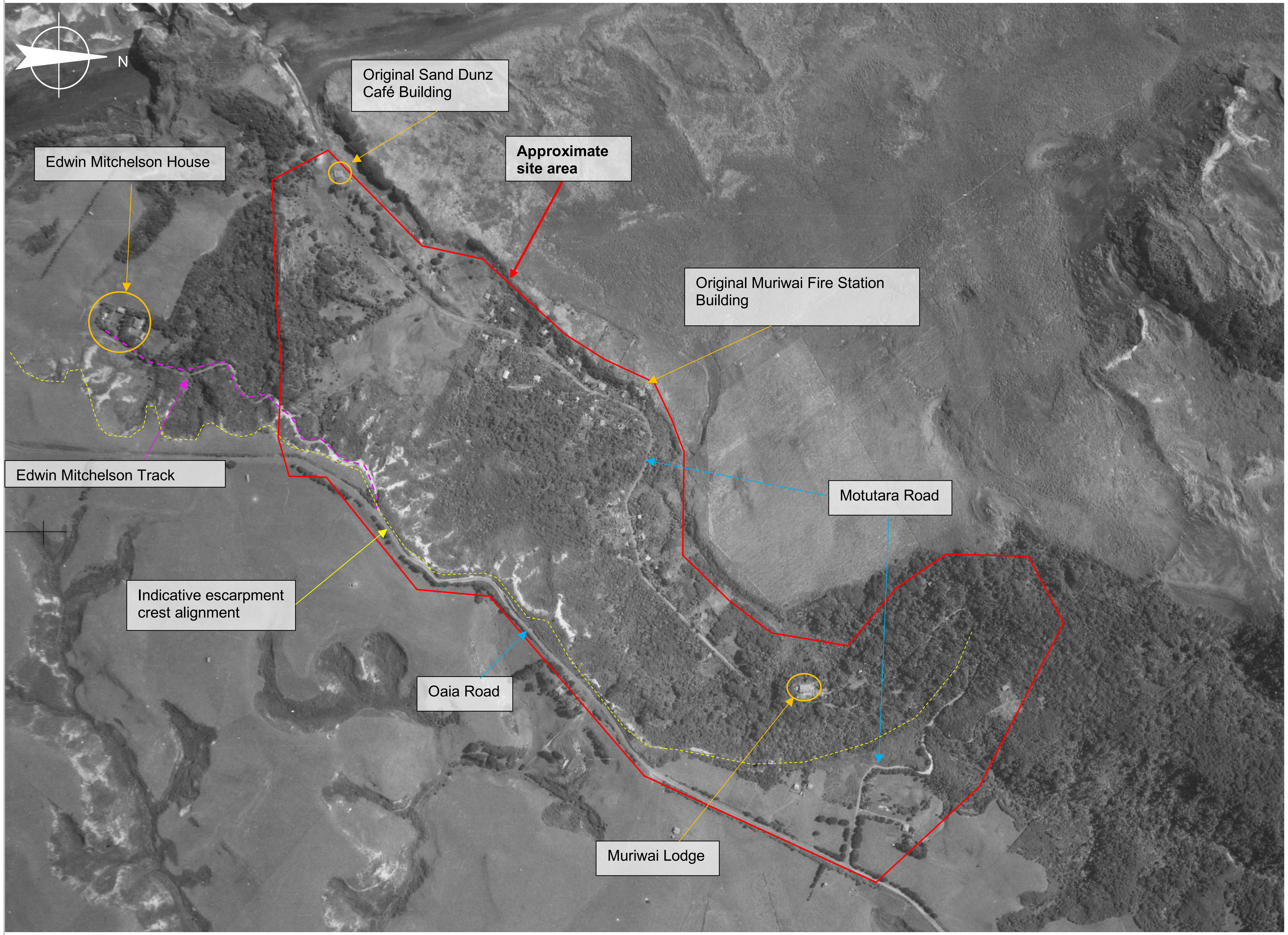
Manawatu Times. 29 Dec 1922. Papers Past | Newspapers | Manawatu Times | 29 December 1922 | HEAVY FLOODS. (natlib.govt.nz) MANAWATU TIMES, VOLUME XLVI, ISSUE 2536, 29 DECEMBER 1922, PAGE 5

Appendices

Appendix B-1

Historical air photograph record

Historical aerial photography

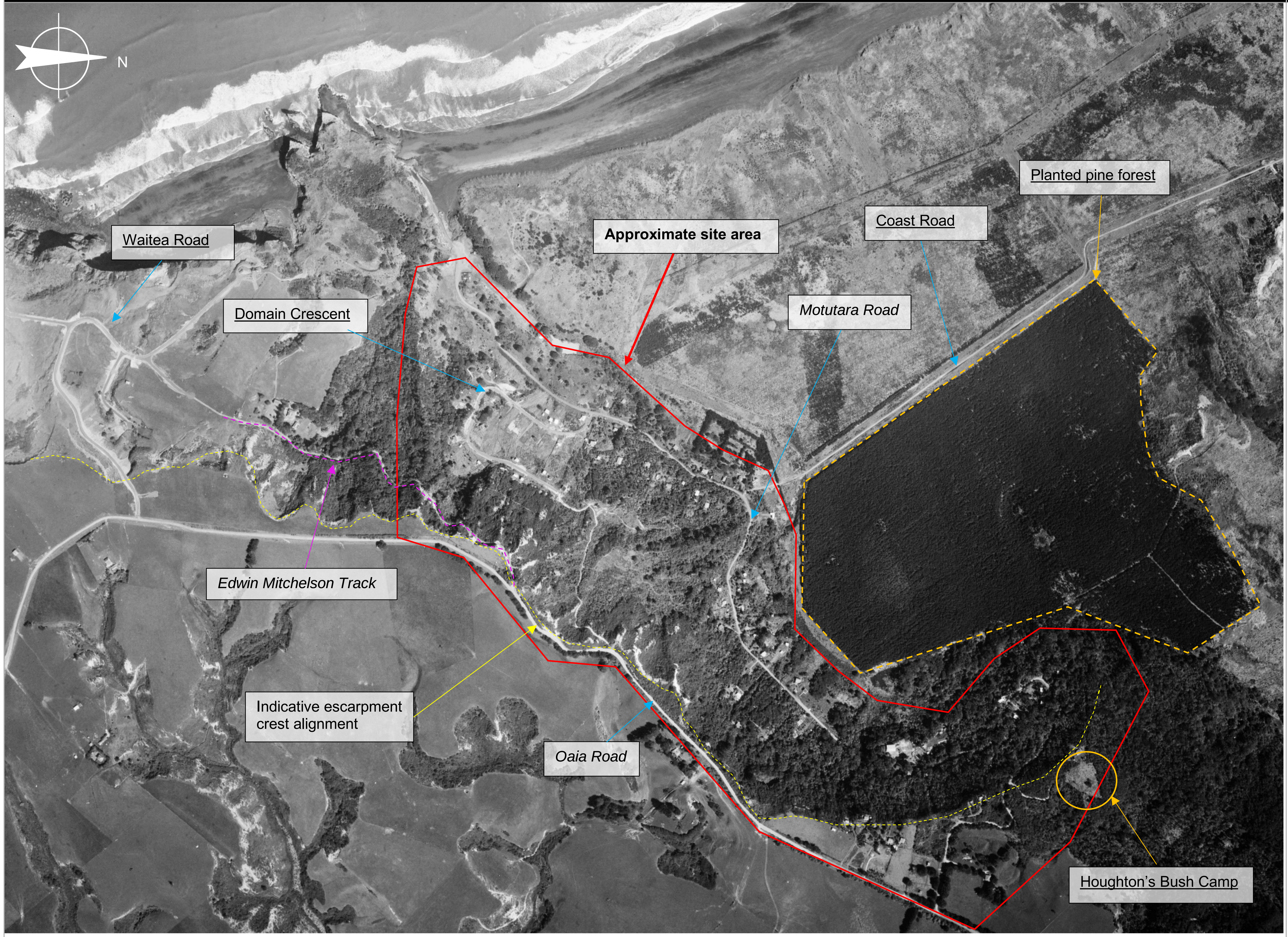


Comments

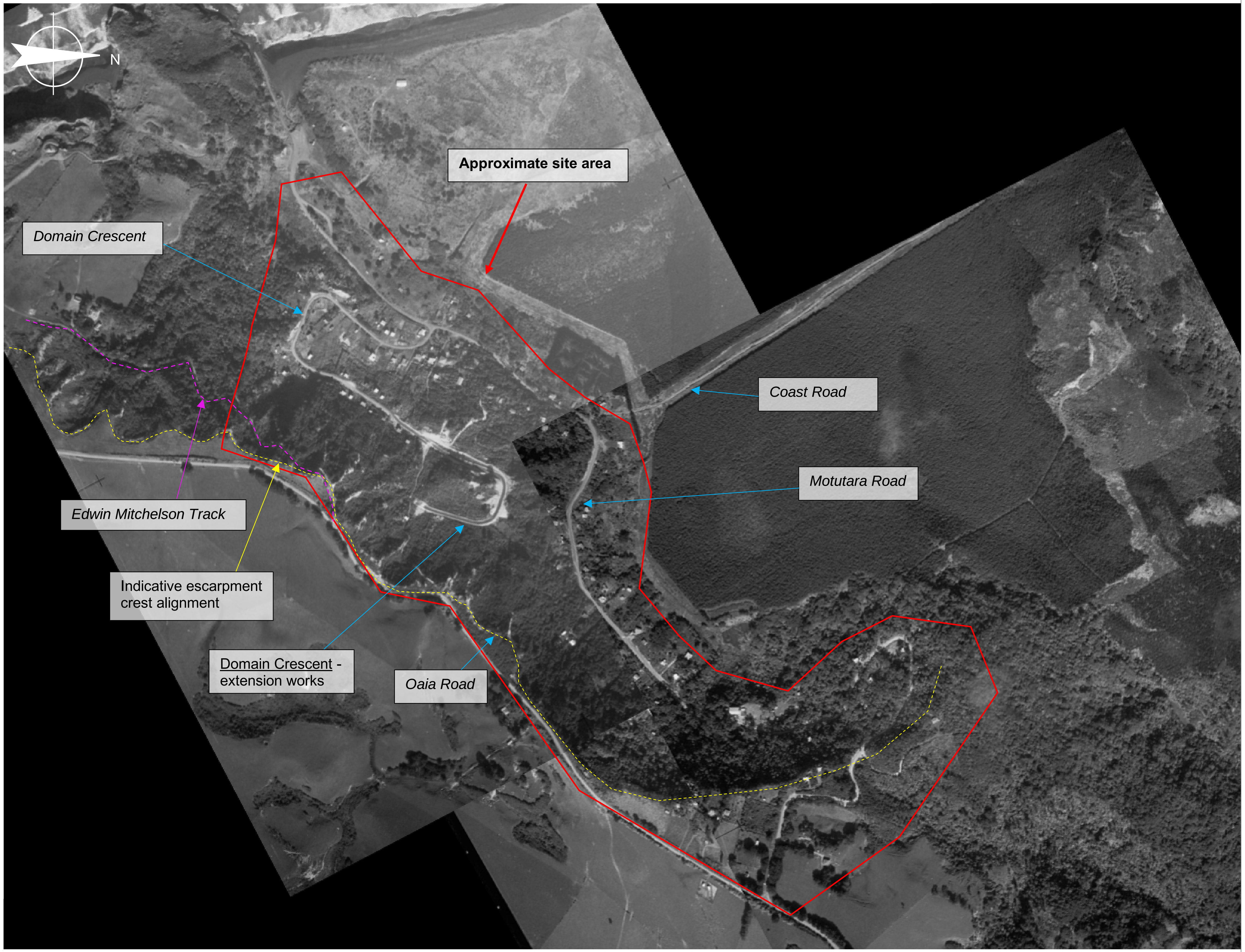
Source: Retrolens
Date: 22/04/1940
Original Scale: 1:16,000
Survey No : SN143
Run #: 93
Photo Number #: 3

Summary of site conditions

- Crest of escarpment clearly visible to immediate west of Oaia Road and extending further south.
- Oaia Road does not extend past Edwin Mitchelson Track.
- Edwin Mitchelson Track forms the driveway to Edwin Mitchelson House.
- Motutara Road has been constructed.
- Very little property development has been undertaken. Several buildings are still present today.
- The southern extent of Muriwai (accessed from Waitea Road) is undeveloped.
- Vegetation (scrub and low bush) extends over most of the project site.
- Erosional "scaring" below escarpment visible.

Historical aerial photography	Comments
	**Source: Retrolens** **Date: 19/09/1950** **Original Scale: 1:15,900** **Survey No #: SN583** **Run #: 1916** **Photo Number #: 3** **Summary of key land use change:** - Increase in property development, as well as the development of Houghton's Bush Camp. - Forest/vegetation development north of the site - Development of Domain Crescent has begun. - Part of Waitea Road has been constructed. - Coast road has been developed from Motutara Road. - Pine forest has been planted adjacent to Motutara Road and Coast Road.

Historical aerial photography



Comments

Source: Retrolens

Date: 22/10/1953

Original Scale: 1:8,400

Survey No #: SN832

Western end:

Run #: D

Photo Number #: 34

Northeastern end:

Run #: C

Photo Number #: 32

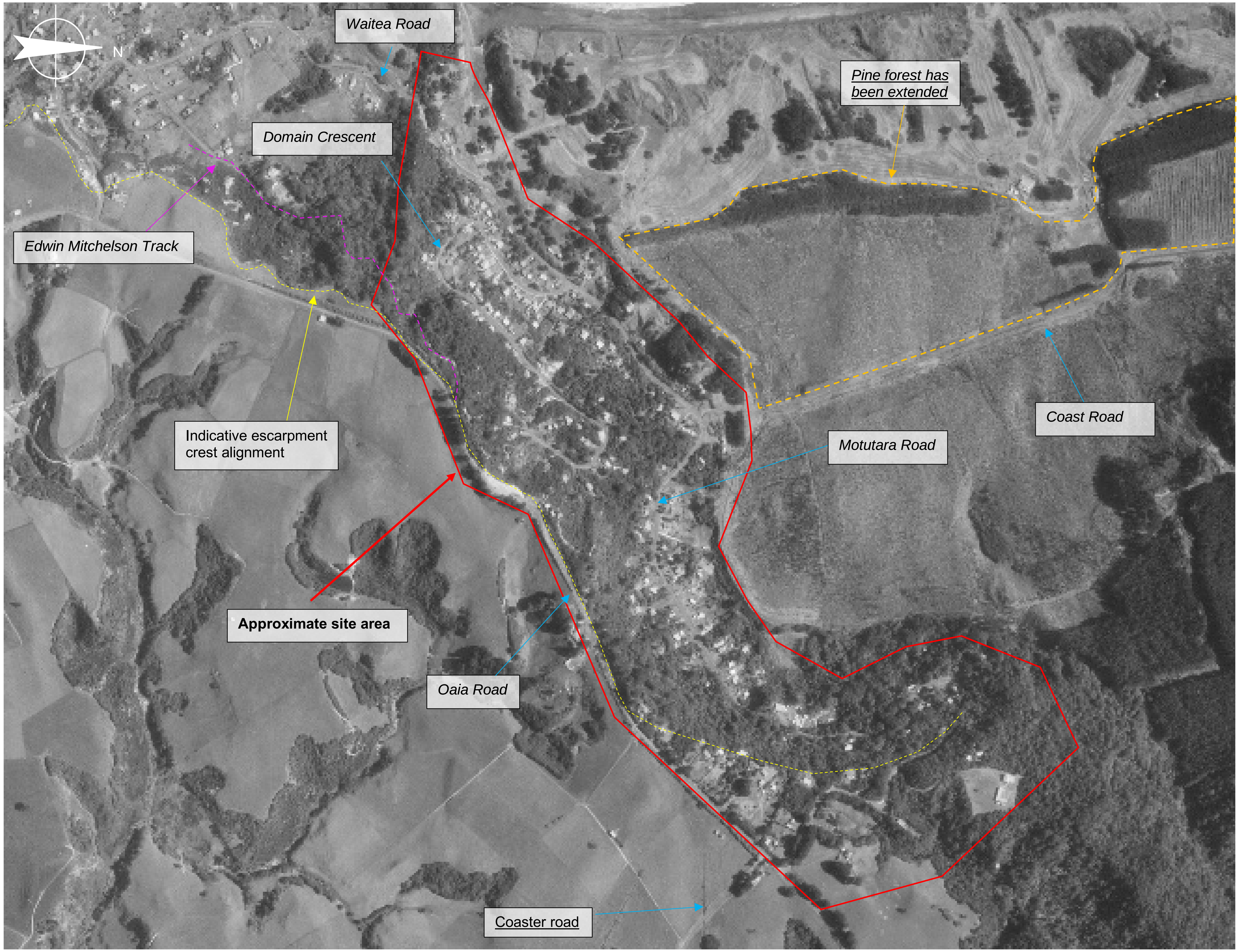
Southeastern end:

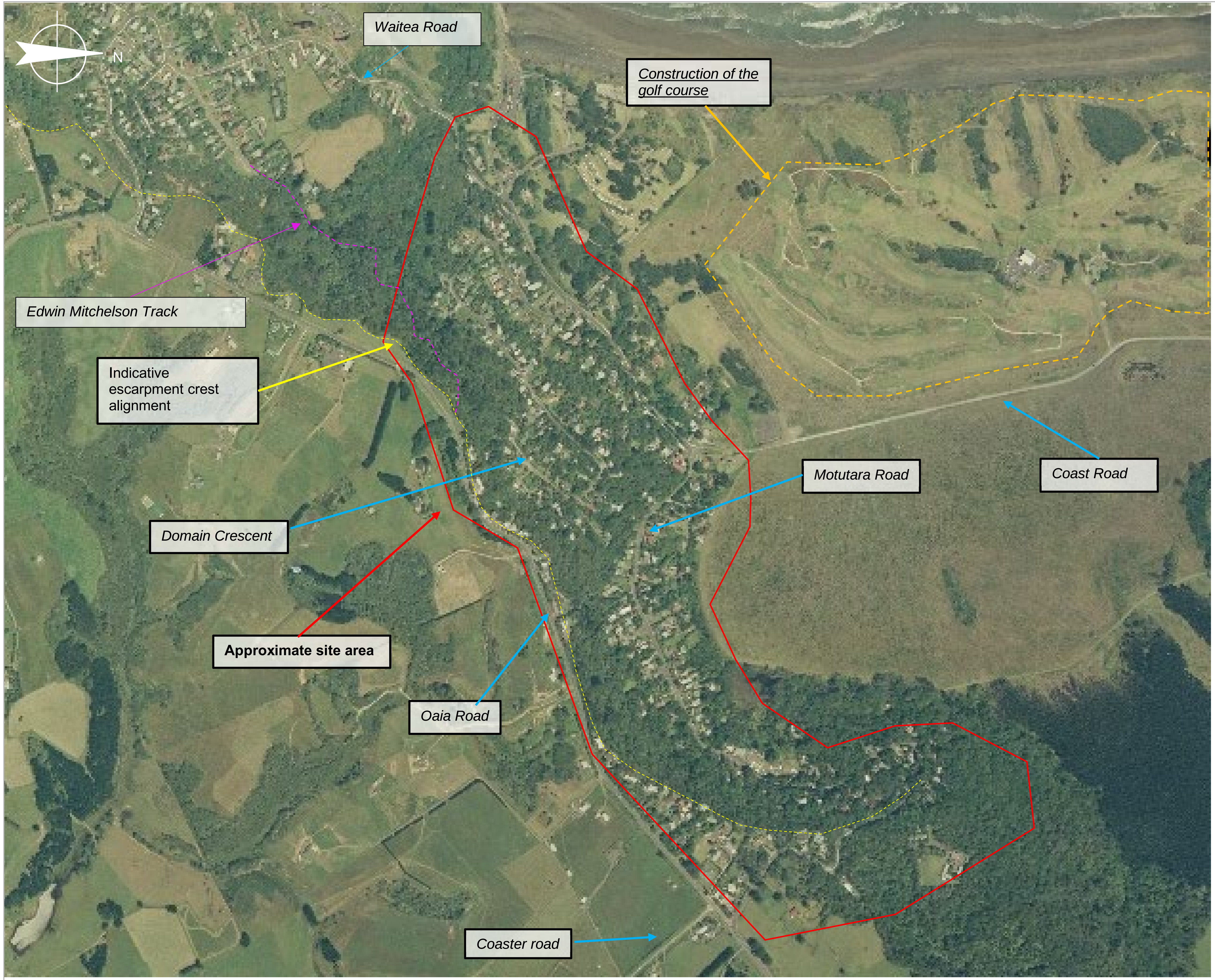
Run #: C

Photo Number #: 33

Summary of key land use change:

- Domain Crescent has been extended to present day location. Associated minor residential development.

Historical aerial photography	Comments
	**Source: Retrolens** **Date: 31/07/1975** **Original Scale: 1:49,000** **Survey No #: SN3800** **Run #: B** **Photo Number #: 3** **Summary of key land use change:** - Two landslides occurred in 1965 between the Edwin Mitchelson track (which is located along the escarpment) and Domain crescent due to blocked water table. - Further property development within the site. Most prominently along Motutara Road. - The current Muriwai Fire Station facility has been established as of 1965. - Waitea Road has been extended and now intersects Motutara Road. - Pine forest has been extended to the west of Coast Road.



Source: Retrolens
Date: 02/01/2004
Original Scale: 1:49,000
Survey No #: SN3800
Run #: B
Photo Number #: 3

Summary of key land use change:

- The pine forest, west of Coast Road has been removed and the golf course has been constructed.
- Increased density of residential housing.

Historical aerial photography	Comments
	**Source: GeoMaps** **Date: 2015-2016** **Summary of key land use change:** - Property development within Domain Crescent. - Minor building constructions outside of the site such as the Muriwai Surf Club and Tennis Courts. - The current business named "The Samd Dunz Beach Café" is registered as of 23 Oct 2014

Historical aerial photography	Comments
	**Source: Google Earth** **Date: March 2023** **Summary of key land use change:** - Recent landsliding visible from satellite imagery. - Pine forest and vegetation along the escarpment is well established.

Appendix B-2

Summary of anecdotal evidence

Information relating to the vicinity of Domain Crescent:

- Noted that individual slopes have not experienced any slope failure or topsoil slips, including from people who have been residents since 1975.
- A small landslip occurred in 2000 on the east side of 60 Domain Crescent. A retaining wall was subsequently constructed in 2006 as part of a dwelling construction.
- The southern area of Domain Crescent below the escarpment (approximate house numbers 51 to 65) was swampy in 1981. In the same area above the dwellings, slope debris has been observed, as have downhill-leaning trees.
- Following February 2023, water seepage has been observed from areas not previously known to have seeped, e.g. in cracks in paved surfaces.
- Numerous seepage points have been noted at the uppermost, eastern end of Domain Crescent on the slope below the escarpment (approximate house numbers 124 to 131). An array of open drains has been installed, most recently in 2018 by Auckland Council. Swampy, saturated ground was noted in areas that subsequently failed in February 2023.
- Reference has been made to the Park Rangers asking local people to clear drains on public land below the escarpment in the 1970s and 1980s.
- Open drains frequently blocked by leaf litter. Some were flowing prior to Cyclone Gabrielle.

Information relating to the vicinity of the escarpment at Oaia Road and north Motutara Road:

- Small, localised landslip below escarpment at north Motutara Road following a 2021 storm.
- Numerous springs within the escarpment at north Motutara Road.
- Some reports of water reticulation pipework directed over the top of the escarpment from Oaia Road properties towards Muriwai. In addition, blockages of public stormwater sumps with vegetation has been observed.
- Tree-fall from was observed from February 2023 storm damage. Some downhill-leaning trees have been observed.

Information relating to the vicinity below the escarpment at Motutara Road.

- In January a small slip was observed on the road below 112 Motutara Road and one further uphill in the bush.
- Mature trees that lean downslope have been observed. Some of these have been felled by homeowners.
- Swampy ground observed at toe of slope on the eastern site of Motutara Road. Some small-scale slips have also been observed in this area.
- Surface water flow east of Motutura Road has been observed with increasing volume from January and February 2023. In some cases these discharge from below buildings and have entrained sediment.
- A spring was observed on the western (downhill) side of Motutara Road.
- In the late 1990s, a stream was observed from Domain Crescent through to 302 Motutara Road. This was later remediated by Auckland Council. A slip was observed on the side of Motutara Road.
- Blocked open drains have been observed. Residents sometimes clear these.
- Stormwater infrastructure was observed to be overwhelmed by February 2023 stormwater flows.
- Localised flooding observed in frequent occurrence (i.e. relatively small) storm events.

We conclude the following from the anecdotal evidence:

- Below the escarpment there are numerous springs and saturated, swampy areas.
- Surface water control has been necessary with open drains for a long period of time. In some cases these have not been maintained, or have been overwhelmed by storm flows, particularly in early 2023.
- There have been numerous indications of shallow slope instability, such as leaning trees or small-scale slips.
- There are no anecdotal reports of large landslides having affected the area between 1965 and 2023, in addition to the published events.

Appendix B-3

Summary of reviewed literature

Source/subject	Summary of key points relevant to this assessment
Wright (1966). Engineering geological review of 1965 Muriwai landslides.	- A severe storm in August 1965 resulted in approximately 200 mm of rain and, two large landslides above Domain Crescent that caused destruction of a house and two fatalities. - Anecdotal evidence suggests the landslide moved as a high velocity, saturated debris flow. Discussion and field observations suggest initial movement of an intact block before near-instantons break down to a liquefied debris flow. - The depth of the slip plane was estimated between approximately 0.5 m and 2.0 m. - Face-seepage of groundwater was observed at mid-slope along the landslide (extending for several days after) and concentrated along bedding plane outcrops with siltstone-sandstone. These may have contributed to the landslide.
Interest NZ (2023) Landslides and law: Cyclone Gabrielle raises serious questions about where we've been allowed to build	- 1965 landslide above Domain Crescent in Muriwai
Press (1965) Mopping up After slips	- 1965 landslide above Domain Crescent
Rodney District Council (2005). Muriwai future planning document dealing with a wide range of considerations including environmental hazard.	- Addresses the implications of the built environment having a negative impact on slope stability natural hazard at Muriwai: removal of stabilising vegetation to support residential growth; addition of low permeability surfaces that increases run off and erosion; lack of reticulated wastewater system, increases ground saturation through septic-systems. - Recommended most of the area below the escarpment and on the escarpment be avoided for construction of residential dwellings without prior geotechnical assessment. - Outlines that the township in its current location is vulnerable to slope stability hazard. - Notes the history of road-side failure/ drop-outs on Domain Crescent - Notes multiple areas of surface stormwater ponding, which are primarily concentrated at the immediate base of the escarpment slope, overlain with residential properties built off Domain Crescent and Motutara Road
Hayward (2022). Summary of 1965 landslip event with focus on two Domain Crescent slips and additional commentary to Wright, 1966.	- Draws additional focus to the mechanism of the 1965 landslide failure; concludes it likely the result of both groundwater surface springs from geological unconformity (per Wright, 1965) but in addition, direct surface saturation near the headscarp from surface flows over-topping the Edwin Mitchelson Track. - Notes that Rodney District Council stated no further development in the area destroyed (surrounding 51-53 Domain Crecent); however, notes that in present day, this has not been adhered too with multiple new dwellings.
Auckland Council (2023). Summary of measured and inferred rainfall accumulation at Muriwai during Cyclone Gabrielle. Reference reproduced in Appendix E.	- Outlines that rainfall in Muriwai was measured via direct rain gauge (tipping bucket 'TP08') however this failed at 1am 14 February due to flooding damage. In addition to this record, a Quantitative Precipitation Estimate was taken, which estimates rainfall intensity and accumulation from rainfall radar data.

	- Data indicates over 130 mm of rain fell at Muriwai over a 12-hour period from 13-14 February. In total, over 180 mm was estimated to accumulate over the Cyclone Gabrielle event. - The recorded figures above exceed the 100-year event return period for a 12-hour duration. - The total rainfall that had been recorded over January (including Cyclone Hale) was approximately seven times the normal accumulated amount for this month in this location (490 mm recorded, compared with 70 mm for normal).
Stuff (2013) Old memories revisited	- 2013 landslide above Domain Crescent in Muriwai
Auckland Star (1934) The deluge. Many floods. Traffic delay.	- 1934 flooding observed of the creek close to Muriwai beach causing a relief workers' camp to flood
Manawatu Standard (1926) Floods in the North. A record rainfall in Waitakere Ranges. Campers in peril at Muriwai	- 1926 flooding observed in Muriwai. A few buildings were flooded and displaced at Motutara Domain. The road approach the beach was washed away, and the campground became untenable.
Evening Star (1926) Record flood. Auckland cloud bursts eight inches of rain in a day.	
Wairarapa Daily Times (1926) Unseasonable weather. Floods in the North.	
Southland Times (1926) Auckland's rain phenomenal fall. The worst for fifty years.	
Christchurch Star (1926) The worst floods for fifty years do damage in North.	
Evening Post (1922) Heavy floods. Auckland trippers caught. [10]	- 1922 flooding cut off traffic access to Muriwai.
Manawatu Times. 29 Dec 1922. Heavy floods. Auckland trippers caught. [11]	

Appendix B-4

Database of observed 2023 landslides

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 2	M-LS01	Translational, Debris flow	1728500.19	5924036.28	36	0.5	142	38	Large landslide has damaged or destroyed multiple structures on multiple properties. A patch of insitu trees is visible.	
	M-LS02	Translational, Debris flow	1728523.55	5923935.03	52	0.5	127	31	Large landslide has damaged or destroyed multiple structures on multiple properties. Landslide debris comprises Awhitu Sand. Patch of Insitu palm trees present within the centre of the landslide	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 2	M-LS03	Translational, Debris flow	1728528.85	5923806.37	33	0.25	91	42	Large landslide above Watercare's water treatment plant on Motutara Road	
	M-LS04A	Translational, Debris flow	1728515.77	5923775.84	26	0.75	116	47	Large landslide with strip of intacted trees down the middle. Spring daylighting near the base of escarpment	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 2	M-LS04B	Translational, Debris flow	1728510.78	5923749.67	27	0.75	151	41	Large landslide with strip of intacted trees down the middle. Spring daylighting near the base of escarpment	
	M-LS05 does not exist. Next landlside is M-LS06									
	M-LS06	Translational, Debris flow	1728361.87	5923509.18	15	0.25	120	27	Three distinct landslides. Spring located towards the base of the slope. A darker confining layer is present below the spring.	

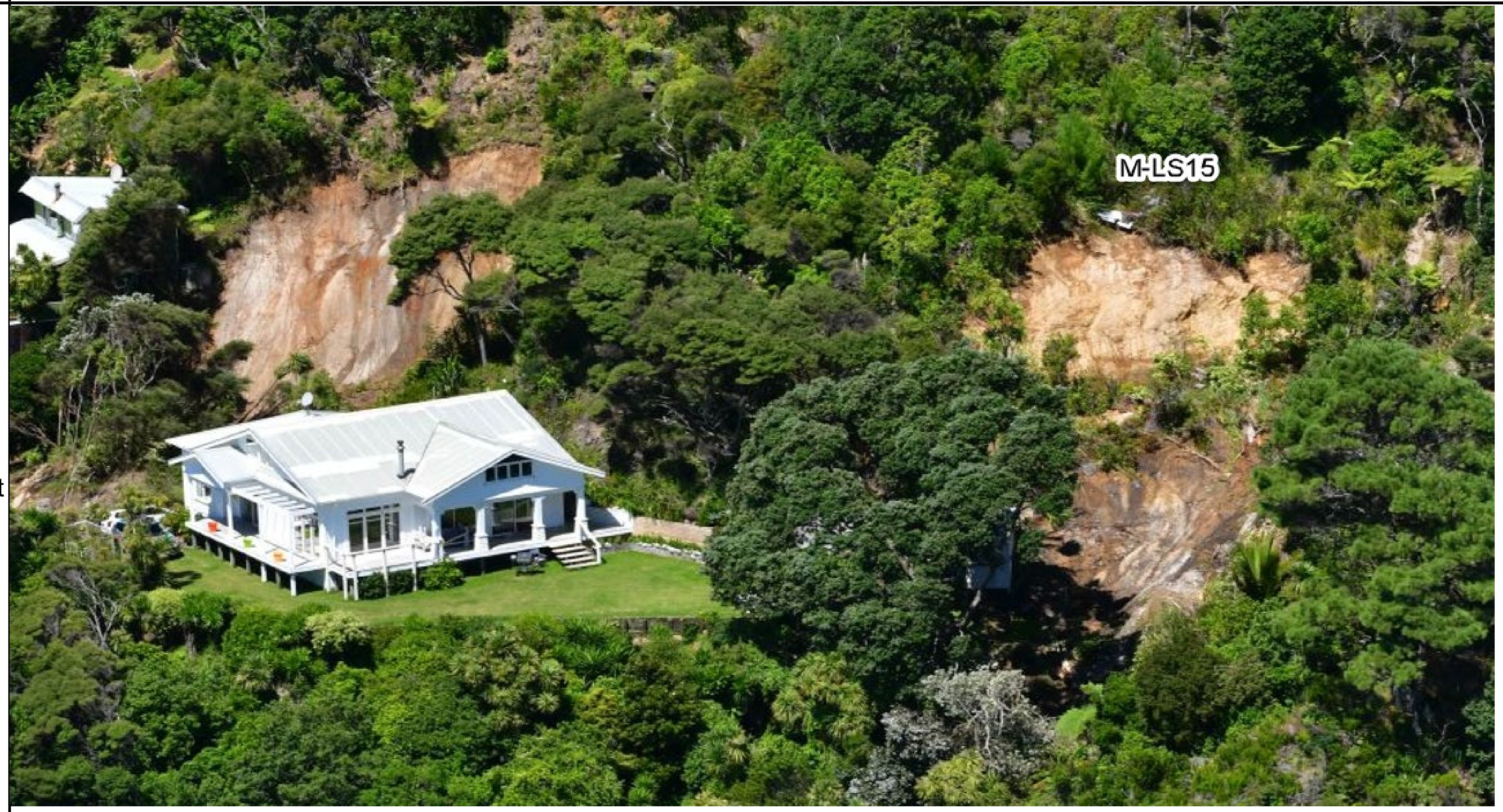
Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 2	M-LS07	Translational, Debris flow	1728341	5923497.96	16	0.25	10	31	Three distinct landslides. Spring located towards the base of the slope. A darker confining layer is present below the spring.	
	M-LS08	Translational, Debris flow	1728314.83	5923503.88	27	0.25	108	40		

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 2	M-LS09	Translational, Debris flow	1728261.56	5923470.24	77	0.75	154	31	Large landslide with amalgamated debris flow at base. Debris comprises Awhitu Sand and vegetation. No observed spring feature, however water was observed on the face of a darker confining layer close to the invert of the base of the slope.	
	M-LS31 and M-LS32 do not exist. Next landslide is M-LS33									
	M-LS33	Translational, Debris flow	1728339.44	5923575.22	8	0.25	26	44	Smaller landslide occurred within dense vegetation, located near the base of the escarpment	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 2	M-LS34	Translational, Debris flow	1728294.58	5923514.47	19	0.25	63	48	A separate landslide downslope of the main escarpment. Two confining ridgelines form the headscarp.	
	M-LS43	Translational, Debris flow	1728425.33	5923631.56	9	1	30	35	Smaller landslide occurred within dense vegetation, located near the base of the escarpment	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 3	M-LS11	Translational, Debris flow	1728087.884	5923389.317	15	0.5	47	25	Landslide has occurred within the cut slope above the driveway.	
	M-LS12	Translational, Debris flow	1728130.018	5923292.121	8	0.5	89	38	A confining layer is present towards the base of the depletion zone with a small spring located above it. The landslide is located on the mid-slope of the escarpment.	

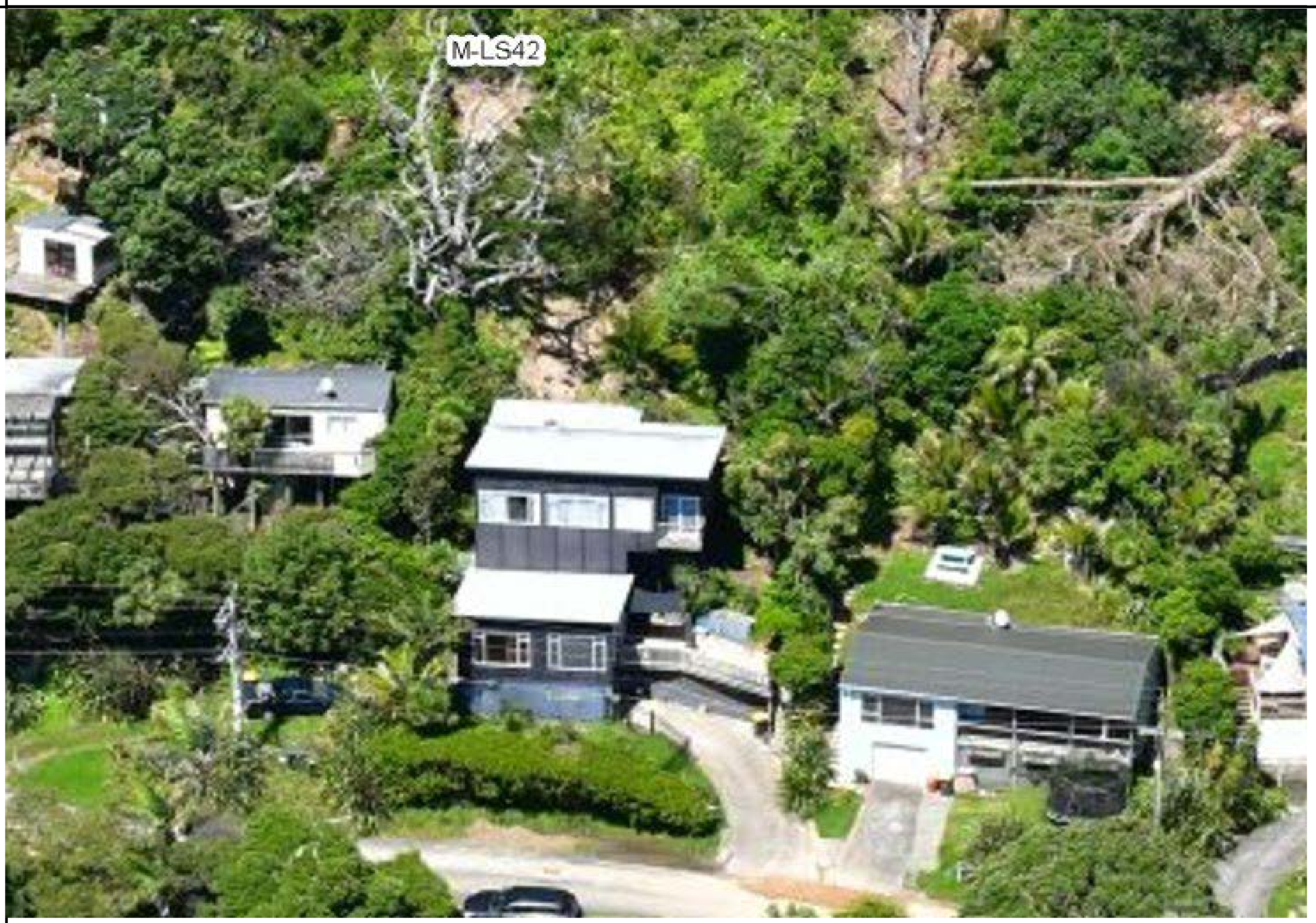
Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 3	M-LS13	Translational, Debris flow	1728038.624	5923223.157	9	0.5	58	28	Cross bedded Awhitu Sand visible in head scarp. Seepage originating from cross bedding is visible. Dark bluish grey clayey material observed 2 m below head scarp.	
	M-LS14	Translational, Debris flow	1728006.382	5923218.951	20	0.5	71	26	Landslide has occurred along a dark bluish grey silty / clayey material. Thickness of this unit in this location is approx. 8 m.	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 3	M-LS15	Translational, Debris flow	1727964.793	5923202.596	15	0.5	47	43	Landslide is located on the mid-slope of the escarpment to the south of the dwelling at 131 Domain Crescent.	
	M-LS16	Translational, Debris flow	1727985.431	5923129.154	19	1	45	27	Intact culvert protruding from the headscarp. Landslide located downslope of the Edwin Mitchelson Track cut (underslip). Middle of slip has been scoured by culvert outlet	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 3	M-LS17	Translational, Debris flow	1727833.251	5923147.612	6	0.5	23	31	Landslide located within the vacant lot. Slip face observes a blocky texture indicating possible block failure manifesting as a debris flow.	
	M-LS18A	Translational, Debris flow	1727924.372	5923021.288	13	0.25	18	55	Landslide has occurred within the upslope cut of the Edwin Mitchelson track (overslip). Track remains mostly intact with some debris on the track.	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 3	M-LS18B	Translational, Debris flow	1727906.46	5923033.905	38	0.5	132	37	Landslide has occurred as an underslip below the Edwin Mitchelson Track. along walking track.	
	M-LS30	Translational, Debris flow	1728143.531	5923377.985	7	0.5	14	46	Small headscarp located behind dwelling at 114 Domain Crescent. Debris locally arrested by house.	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 3	M-LS35	Translational, Debris flow	1727947.192	5923160.384	23	0.5	81	39	Inaccessible by foot - mapping was caried out using aerial photography.	
	M-LS36 to M-LS40 do no exist. Next landlside is M-LS41									
	M-LS41	Translational, Debris flow	1727953.227	5923371.054	14	1	8	55	Landslide has occurred as an overslip within the road cut of Domain Crescent.	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 3	M-LS42	Translational, Debris flow	1727907.628	5923229.037	4	1	25	40	A landslide has occurred behind and upslope of the dwelling. The landslide has occurred on the slopes toward the lower base of the escarpment.	
Zone 4	M-LS19A	Translational, Debris flow	1727917.791	5922983.788	49	0.5	25	55	Landslide has occurred within the upslope cut of the Edwin Mitchelson track (overslip). Track remains mostly intact with some debris on the track.	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 4	M-LS19B	Translational, Debris flow	1727875.58	5922999.209	38	0.25	115	27	Landslide has occurred as an underslip adjacent to the Edwin Mitchelson track cut. Seepage observed above limonite layers	
	M-LS20A	Translational, Debris flow	1727848.788	5922938.305	46	0.5	13	55	Landslide has occurred within the upslope cut of the Edwin Mitchelson track (overslip). Track remains mostly intact with some debris on the track.	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 4	M-LS20B	Translational, Debris flow	1727820.128	5922964.941	96	0.75	137	42	Landslide has occurred as an underslip adjacent to the Edwin Mitchelson track cut. Seepage observed above limonite layers	
	M-LS21	Translational, Debris flow	1727721.219	5922970.237	18	0.25	57	49	Landslide has occured within the slopes behine the dwelling. Relatively shallow failure of residual soil with some of the underlying intact blocks of cemented sand. Approx. 1m thick. Debris very close to slope base, arrested by house on property 47. scarp exposes a 2 m thick bed of white siltys and, with slight NW dip.	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 4	M-LS22	Translational, Debris flow	1727698.555	5923022.184	23	0.25	17	53	Landslide has occurred as an overslip within the road cut for Domain Crescent. Relatively shallow <1m depth. Visible cross bedding in 10 cm horizons. finer grained/massive texture.	
Zone 5	M-LS23	Zone 4	1727675.035	5922958.321	40	0.5	30	49	Landslide has occurred within the slopes behind the dwelling. Headscarp is located along the confining local ridgeline	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 5	M-LS24	Translational, Debris flow	1727573.789	5922959.879	12	0.25	39	32	Landslide within Awhitu Sand has displaced minimal soil and mostly comprises vegetation. Significant scour observed within the escarpment.	
	M-LS25	Translational, Debris flow	1727554.474	5922953.181	8	0.25	42	31	Landslide was not physically accessible, as such was mapped using aerial photography and lidar.	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 5	M-LS26	Translational, Debris flow	1727561.406	5923078.92	8	0.51	9	39		
Zone 6	M-LS10	Translational, Debris flow	1728207.043	5923480.828	19	0.25	52	37	Groundwater seeping out of escarpment in multiple locations. Less cemented sand present for most of slip. The landslide has manifested as a debris flow and impacted the dwelling at 232 & 230 Motutara Road	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 6	M-LS27	Translational, Debris flow	1728026.436	5923507.502	19	0.25	35	26	White silty fine white sand exposed. An open watercourse is present at the base of the gully	
	M-LS28	Translational, Debris flow	1727970.984	5923538.966	11	0.5	20	31	Landslide has occurred off a spur off the main escarpment	

Appendix B-5

Survey data used for GHD analysis and plans

The survey data used by GHD for data presentation and modelling used the following datasets:

- 2016 LiDAR elevation model (Muriwai_dtm_2016)
  - Source: Auckland Council
  - Point cloud accuracy is vertical <= 0.10 m RMS and horizontal <= 0.30 m RMS
- 2016-2018 LINZ DEM (Auckland North LiDAR 1 m DEM)
  - Source: **Auckland North LiDAR 1m DEM (2016-2018) | LINZ Data Service**[4]
  - Vertical Accuracy Specification is +/- 0.2m (95%), Horizontal Accuracy Specification is +/- 0.6m (95%).
- 2023 Muriwai elevation model (Muriwai_dtm_20230304_calibrated_internal).
  - Source: Auckland Council
  - Metadata: **Specified Auckland Areas Post Cyclone LiDAR Point Cloud | Auckland Council Open Data (arcgis.com)**[5]

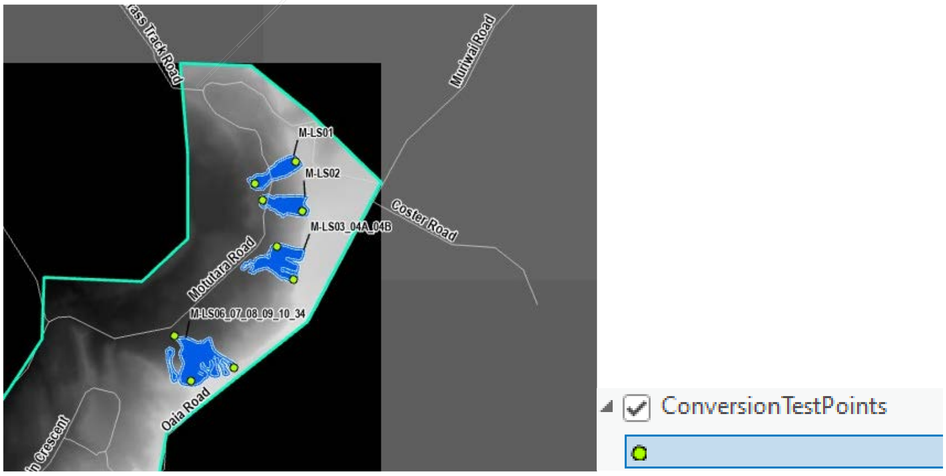
The 2023 Muriwai DTM does not state the vertical datum in the metadata. However, AC have advised the DEM was in NZVD2016 vertical datum.

The 2016 elevation DTM did not have a vertical datum attributed, however the AAM metadata for the 2016-2017 Auckland Council LiDAR data collection mentioned that all products are supplied in Auckland 1946 vertical datum and point cloud products are also supplied in NZVD2016 vertical datum.

As the 2023 elevation data was stated as being in NZVD 2016 and the Auckland DEM from LINZ has metadata stating it to be in NZVD2016 the 2016 DEM from LINZ was selected for raster calculations.

A sample set of 9 points across the landslide areas was created to cross check for differences in elevation. It was noted across this sample set that the Muriwai_dtm_2016 was showing elevation values that were consistently 0.29 m (2 dp) greater than the elevation value off the LINZ DEM confirming that it was in Auckland 1946.

A further check of the 9 sample points by using the LINZ online converter (**New Zealand Vertical Datum Conversions (linz.govt.nz)**) to convert the Muriwai_dtm_2016 elevation values at those sample points to NZVD 2016 using the online converter and comparing them to the values in the LINZ DEM. The average difference was 0.001 (3 dp). This indicated that substituting the LINZ DEM in lieu of converting the Muriwai_dtm_2016 was not going to result in any elevation differences that was likely to affect our interpretations of raster calculations. Also noting this calculated average difference was much smaller than the vertical accuracies stated for the LINZ DEM (+/-0.2m) and Muriwai_dtm_2016 (<=0.1 m).



---

[4] Auckland North LiDAR 1m DEM (2016-2018) | LINZ Data Service

[5] Specified Auckland Areas Post Cyclone LiDAR Point Cloud | Auckland Council Open Data (arcgis.com)

ghd.com

→ The Power of Commitment

Appendix C

Slope Stability Report

Waitakere Coastal Communities Landslide Risk Assessment

Appendix C – Muriwai Slope Stability Assessment Report

Auckland Council

30 April 2024

→ **The Power of Commitment**

Project name	AC Geo Panel - Waitakere Coastal Communities LHRA
Document title	Waitakere Coastal Communities Landslide Risk Assessment | Appendix C – Muriwai Slope Stability Assessment Report
Project number	12612462
File name	12612462_Appendix C SlopeStability_FINALRev1.docx

Status Code	**Revision**	**Author**	**Reviewer**		**Approved for issue**		
			Name	**Signature**	**Name**	**Signature**	**Date**
S4	0	T Khansari	D Macfarlane	DMacfarlane	Roy Pearson	Roy Pearson	30/04/2024
[Status code]							
[Status code]							
[Status code]							
[Status code]							

GHD Limited
Contact: Matt Howard, Technical Director - Engineering Geologist | GHD
27 Napier Street, GHD Centre Level 3
Freemans Bay, Auckland 1010, New Zealand
T +64 9 370 8000 | **F** +64 9 370 8001 | **E** aklmail@ghd.com | **ghd.com**

Contents

Table index

Figure index

Appendices – Slope stability analysis output figures

C1. Introduction

C1.1 Purpose of this Report

GHD has been engaged by Auckland Council (AC)[1] to carry out landslide risk assessments as well as to provide associated landslide risk management advice and geotechnical investigations in the Waitakere area, specifically for the residential areas of Muriwai, Piha and Karekare.

The purpose of this report is to present a slope stability and back analysis assessment of one of the large, failed slopes at the escarpment to the east of Muriwai township. The objective of the analyses was to estimate rock or soil strength parameters that could be used to inform conceptual remediation options to demonstrate the engineering measures required to stabilise the escarpment.

A two-dimensional Limit Equilibrium Analysis was carried out to estimate material parameters applicable to the failed zone. The analysis has also assessed the influence of changing pore pressure levels. The seismic performance of the slopes was also assessed, considering factors such as design life, site soil class, peak ground acceleration, and compliance with the NZ Building Code. We have considered commonly acceptable mitigation approaches and provided rough cost estimates for implementing the options investigated.

Figure C-1 shows the site location and the mapped landslides in the area.

---

[1] Under Contract CW198379, Master Services Agreement CCCS: CW74240 dated 7/09/2019

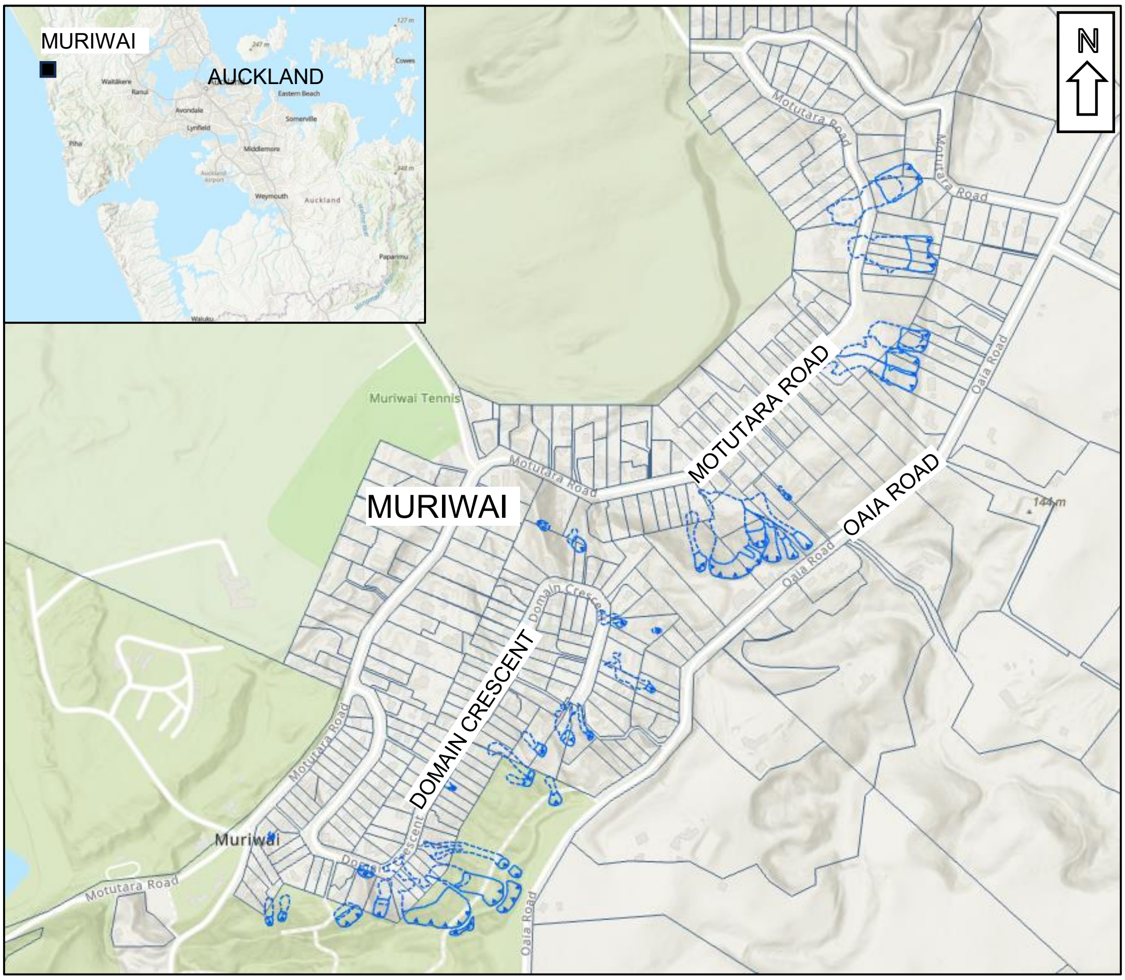


Figure C-1 ***Muriwai location showing the February 2023 landslides mapped by GHD (blue lines)***

C1.2 Scope

The following scope of works has been undertaken:

- Conduct back analyses using Slope/W on recently failed slopes in Muriwai to derive material parameters for the assessment of remedial options.
- Quantify the sectional area of landslides by overlaying pre- and post-failure ground profiles.
- Perform a sensitivity analysis on moisture levels within the slope to assess their impact on slope stability, comparing with rainfall data.
- Explore mitigation options for the escarpment below Oaia Road based on the stability analysis results, targeting a Factor of Safety of 1.5 or greater for static analyses and a target Factor of Safety of unity for Damage Control Limit State seismic cases.
- Assess the seismic performance by determining the Importance Level, assigning Site Soil Class, deriving a Peak Ground Acceleration, and ensuring compliance with the NZ Building Code.
- Consider the NZ National Seismic Hazard Model for updated guidance.
- Exclude simultaneous occurrence of extreme weather events and large earthquakes. The coinciding of two such low probability events is not required by design codes.
- Examine a flatter benched profile and soil nailing with inclined drains as remedial options.
- Provide hand sketches and cost estimates for the proposed mitigation options.

This technical memorandum has been prepared by GHD for Auckland Council. This memo should be read in conjunction with all other GHD design documentation for the project.

C2. Report Structure

The accompanying GHD Engineering Geology report provides a detailed description of the site as well as discussion of site geology and geomorphology, historical landsliding, landslide mapping, landslide classification and slope processes. The reader is advised to consult the accompanying GHD reports for further information not contained herein.

Table C-1 presents a summary of the figures referred to in this report (see Appendix A of the overall report).

Table C-1 Summary of accompanying Muriwai landslide risk assessment reports

Report Section	Description
Overall Report	Waitakere Coastal Communities Landslide Risk Assessment (Muriwai)
Appendix A	Figures
Appendix B	Engineering Geological Report
Appendix C	*Slope Stability Assessment Report (this report)*
Appendix D	RAMMS debris flow analysis
Appendix E	Landslide Risk Assessment
Appendix F	Geotechnical Investigations Report
Appendix G	Geotechnical Laboratory Testing Report

C3. Geotechnical Information

C3.1 Representative Cross Section

The cross section shown in Figure C-2 was selected for assessment purposes as being a conservative (i.e. steep) example of the range of failure geometries. The cross-section extends for approximately 260 m horizontally approximately 100 m vertically. A comparison of landslide cross section profiles is presented in Figure C-3.

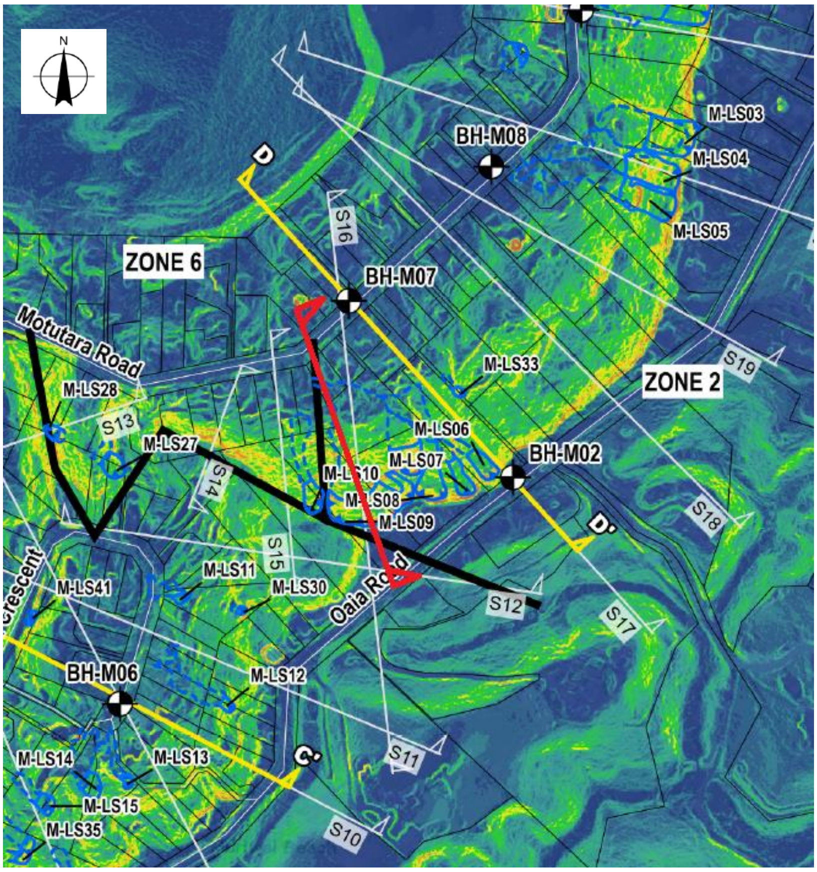


Figure C-2 ***Assessment area plan indicating the major February 2023 slip areas and the analysed cross-section A-A (retrieved from Google Earth Pro and GHD Atlas). A close-up view of Figure A125 (see Appendix A) showing the analysed cross section 'A' relative to other slope profiles, cross sections and boreholes.***

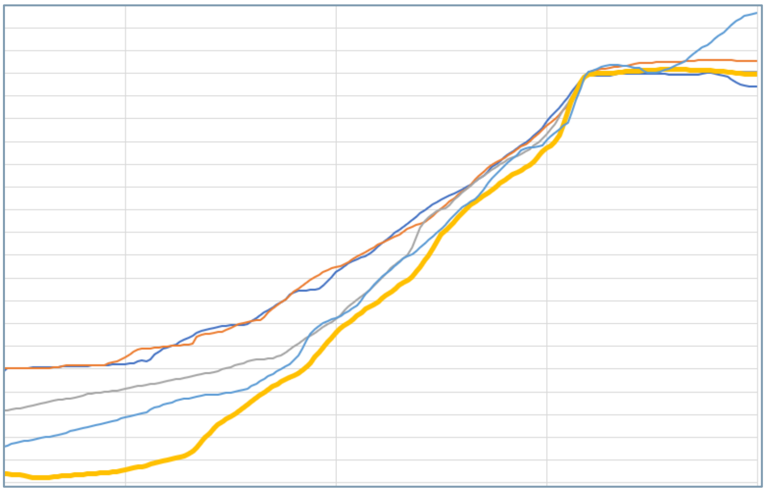


Figure C-3 Indicative comparison of cross section slope profiles at February 2023 landslide sites. The slope profiles at the upper slope have a similar geometry. The thick orange line is the analysed profile.

C3.2 Ground Model

This analysis preceded detailed site mapping and subsurface investigations by GHD (see Appendix B of the GHD landslide risk assessment). Based on initial site observations and the published literature, we have modelled the slope as Awhitu Group comprising the following:

- Weakly cemented sand (sandstone) with localised silt/clay. This comprises the upper three-quarters of the slope profile. This area was the initiation point of the landslides.
- A lower, relatively stronger sandstone. Field observations indicate that the lower slope was relatively stable.

This is consistent with the companion Engineering Geological report (Appendix B) and the 1:250,000 published geological map (Edbrooke 2001).

For the purposes of our analysis, we have made a nominal subdivision with weaker sandstone overlying a higher strength sandstone.

We employed Ru values to model varying degrees of saturation as an alternative to groundwater level, which was unknown at the time of landsliding in February 2023.

The ground model is shown in Figure C-4.

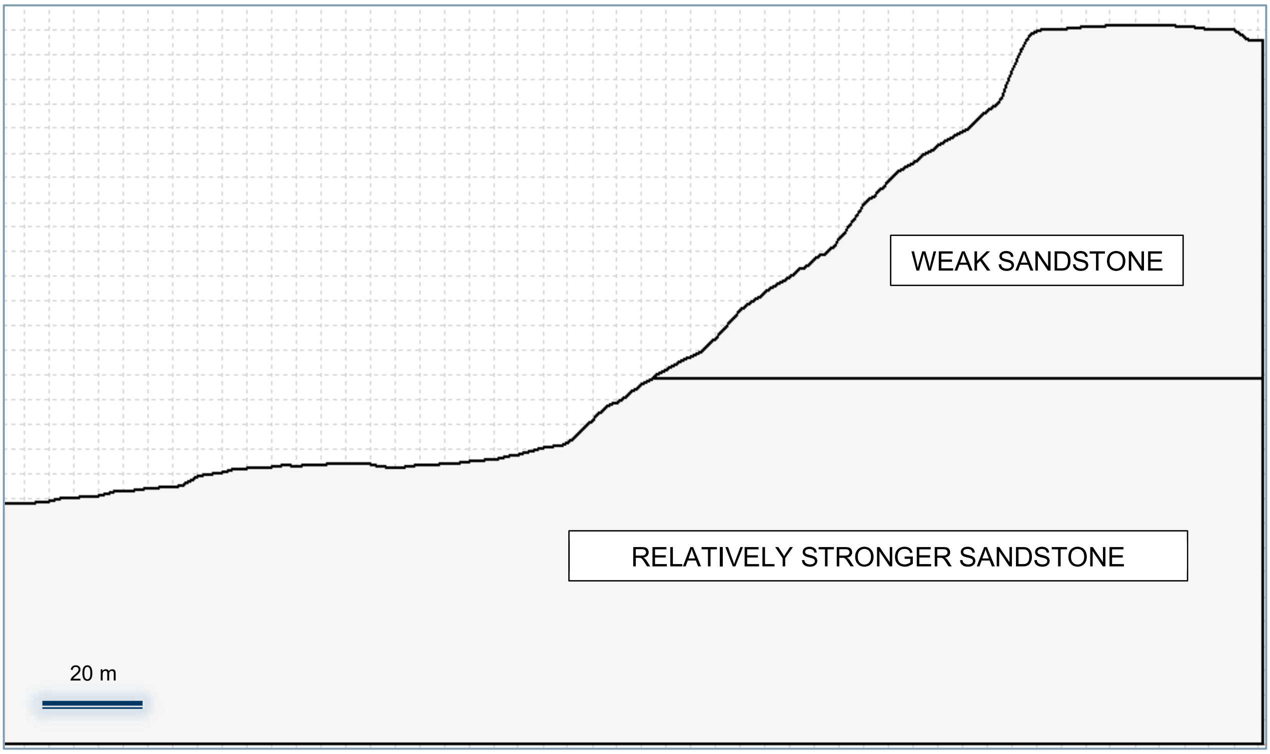


Figure C-4 *Simplified ground model used for the analyses*

C4. Analysis

C4.1 Introduction

The February 2023 landslides occurred during heavy rainfall that caused elevated, destabilising pore-water pressures. The failure surface is characterised by its shallow depth, yet it spans a significant horizontal distance and reaches high elevations, as shown in the Appendix.

Slope stability analyses were carried out using Slope W version 2021.3 (a GeoStudio Package). As part of the back analyses and feasibility assessments, we examined circular, non-circular, shallow, and irregular user-defined slip surfaces. We also employed Ru values to model varying degrees of saturation. The Morgenstern-Price method was chosen as it is suitable for analysing slope stability problems with these features.

C4.2 Back Analysis and Pore Pressure Sensitivity Assessments

The methodology adopted for the back analysis was as follows:

1. The slip to be examined was assumed to have occurred solely within the upper, weaker Kahu Sand weakly cemented sandstone.
2. A single set of c-phi effective stress parameters was assumed to be applicable.
3. No foliation or structural anisotropy was considered applicable.
4. As the failure occurred following heavy rain, we varied Ru within the slope stability model from what is considered to be a “steady state / typical long term” value of 0.125 to relatively highly saturated values of 0.25 to 0.35. We assumed these latter values to be representative of pore pressure levels that may exist after a period of prolonged and heavy rain.
5. In order to derive the geotechnical parameters, we fixed the phi value at 39 degrees. This is considered to represent an upper bound value that may be assigned to a naturally occurring granular material.
6. With the phi value fixed, the effective cohesion was varied until Factors of Safety were derived indicating a progression from marginal stability to “failure” as the Ru value was increased.

Table C-2 shows the results of the sensitivity analysis as Ru was increased. It will be seen that at an Ru value of 0.3, failure of the slope effectively occurs. This is an indication that the parameters utilised are providing reasonable agreement with observed behaviour.

Table C-2 Slope stability sensitivity analysis by modification of Ru for Φ’ = 39 degrees and c’ of 21 kPa

Ru adopted	FoS derived
0.125	1.24
0.150	1.20
0.200	1.12
0.250	1.03
0.300	**0.95 (slope failure)**
0.350	**0.87**

Table C-3 confirms the parameters derived for the Awhitu Sand from the back analysis. These are considered acceptable for a cemented sand. They align well with the ranges provided in publications (e.g., Collins & Sitar 2009). These then, were the geotechnical parameters carried forward to the analyses examining remedial works. Results from the back analyses are included in Appendix C1.

Table C-3 Geotechnical parameters

Material description	**Unit weight (kN/m^3)**	**Effective cohesion c' (kPa)**	**Angle of internal friction Φ' (°)**
Weak sandstone	18	21	39

C4.3 Seismic Analysis

The seismic demand was derived in accordance with the New Zealand Bridge Manual (2022). The peak ground acceleration (PGA) for slope stability analysis was determined using the equation below:

$$PGA = C_{0,1000}\frac{R_u}{1.3}fg$$

NZTA Bridge Manual (2022), Section 6.2.2

Where the coefficients are provided in Table C-4 and g is 9.81 m/s2.

Table C-4 Peak ground acceleration (PGA) derivation parameters for slope stability seismic case

Parameter / Variable	**Value**	**Source**
Design life	50 years	Client-specified
Importance Level (IL)	3	NZS1170.0:2002, Table 3.2.
Annual probability of exceedance for the ultimate limit state for earthquake actions (DCLS)	1/1000	NZTA Bridge Manual, Table 2.3
Subsoil class	Likely D as the sand is ~100 m deep. Intrusive site investigation is being employed to help with ground profiling.	NZS1170.5:2004, Clause 3.1.3.2 – 3.1.3.6
1000-year return period PGA coefficient (C0,1000)	0.19	NZTA Bridge Manual, Table C6.1
Return Period Factor (Ru)	1.3	NZS1170.5:2004, Table 3.5
Site subsoil class factor (f)	1.0	NZTA Bridge Manual, Clause 6.2.2

Based on the above, the PGA is determined to be 0.19 g, which aligns with the PGA values for the ULS case in Auckland for a range of return periods of 500 to 2500 years given in Appendix A of Module 1 (MBIE, November 2021).

C5. Examination of Remediation Options

C5.1 Purpose of Options Assessment

The purpose of conceptual remedial measures is to provide the indicative effort required to inform discussion of whether mitigating debris flow would be practical. It is intended to provide information on two options that may be used to increase slope stability. Other engineering options are available, but exploring these is outside the scope of our work.

C5.2 Proposed Remedial Measures

Two potential remediation options have been examined. These are:

a) Strengthening the slope by using soil nails and inclined drains
b) Excavating the slope to a flatter, more stable, benched profile that satisfies New Zealand code-based stability criteria.

Details of the work carried out to examine their feasibility follows.

C5.3 Options Examined - Discussion

C5.3.1 Soil nails

The following design elements have been considered:

- No shotcrete facing.
- Installation of drains to reduce the pore water pressure within the slope.
- Nails to be installed by roped access method involving small, portable rigs similar to that shown in Figure C-5.
- Surface erosion prevention matting is installed to prevent loss of material at the surface from the space between the nails (see Figure C-6).

Figure C-5 Example of typical small, roped access rig used to install anchors or nails on steep slopes.

Figure C-6 **Example of surface erosion prevention matting and mesh for use with soil nails on relatively steep slopes.**

Soil nail feasibility calculations were carried out in accordance with the following guidance document:

- FHWA. Geotechnical Engineering Circular No. 7 - Soil Nail Walls. 2015 (FHWA-NHI-14-007)

The recommended minimum Factors of Safety for "Overall Stability" for this option requires the following Factor of Safety:

- For Static Loading = 1.5
- For Seismic Loading = 1.1

The soil nail array derived satisfying the above criteria is shown in the Figure C-7 below. To facilitate initial pricing of the option, details of the key materials, quantities and spacings proposed are shown in the Table C-5.

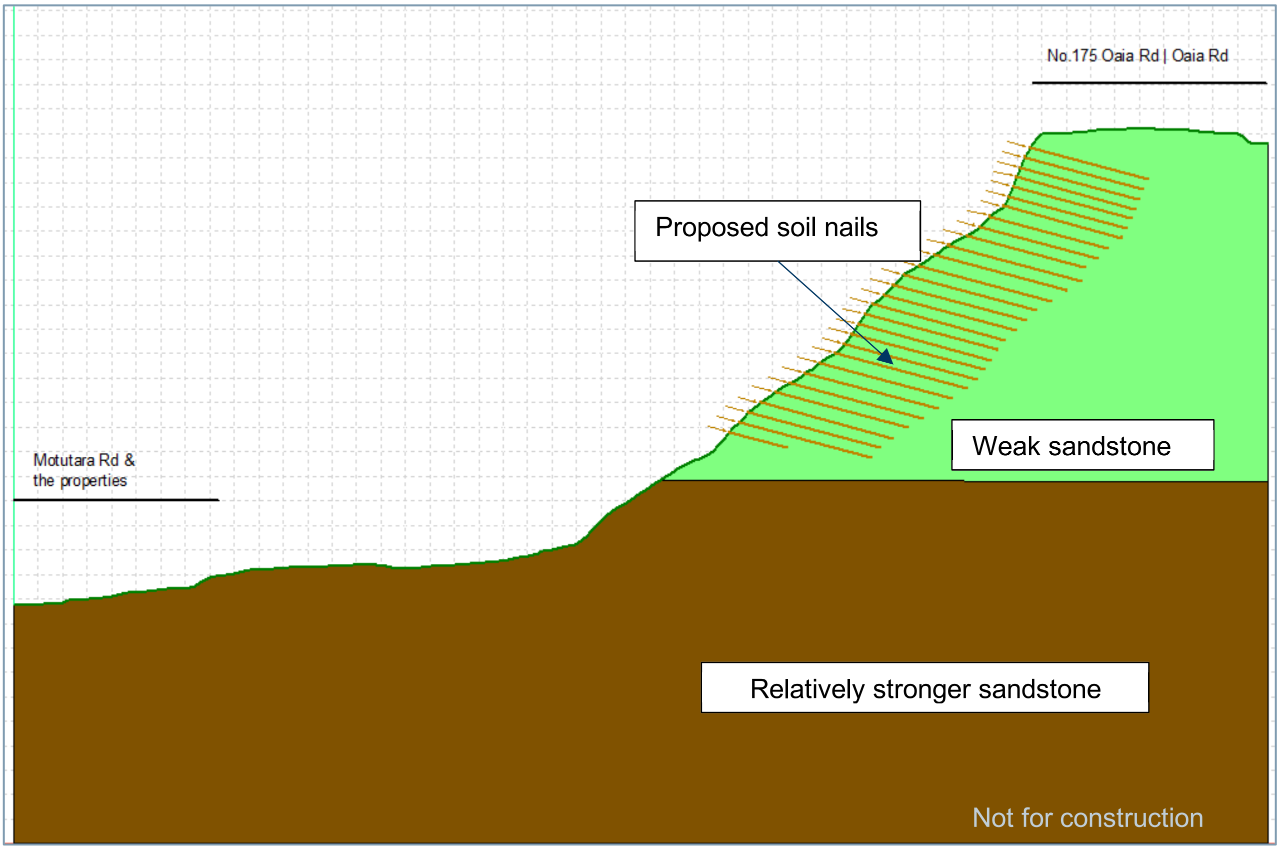


Figure C-7 Soil nail option

Table C-5 Soil nail option – materials, quantities and spacings proposed

Soil nail length (m)	Number of nail rows	Grid (m x m)	Steel bar diameter (mm)	Grade (MPa)	Bond diameter (mm)
28	30	2.0 x 2.0	25	500	120

Construction of the soil nailed option would need to include, but not be limited to, the following processes:

- Obtaining of any necessary easements if the nails were to extend over private property boundaries
- Vegetation removal and/or trimming as required
- Clearing the slope face of any debris or loose material
- Installation of the soil nails via the roped access method chosen
- Installing inclined drains to alleviate the soil pore pressure

C5.3.2 Benched profile

The solution examined has assumed the use of benches nominally 5 m high, each with a horizontal platform of approximately 4 m width. It is assumed that the face of each bench will be sloped back at 2 vertical to 1 horizontal. Although not an essential requirement of the design, inclined drains may also be employed with this option to increase stability.

Conventional, relatively large plant could be used to construct this option employing a “top-down” methodology. For safety reasons, the plant used would be set back at a suitably safe distance from the edge of the slope edge as the works progress downwards.

The option derived involves cutting the crest of the slope back by a horizontal distance of 20 m.

The volume of material to be removed under this option would be approximately 320 m3 per linear metre of remediated slip. The benching layout is shown in Figure C-8.

The stability calculations for this option were carried in accordance with the NZTA Bridge Manual (2022), which also satisfies the Auckland Code of Practice for Land Development and Subdivision (2023) requirements.

The recommended minimum Factors of Safety for “Overall Stability” for this option requires the following Factor of Safety:

– For Static Loading = 1.5
– For Seismic Loading = 1.0

Analysis results are included in Appendix C3.

Note on displacement-based acceptance criteria:

For seismic analyses, the NZTA Bridge Manual allows for displacement-based acceptance criteria for infrastructure such as filled embankments and other earthworks. For the landslip examined, and in particular the benching option, we considered that displacement-based acceptance criteria would not be suitable. This is because, unlike an embankment constructed from engineered granular material, there is more uncertainty regarding the geology and behaviour in a slope cut in natural materials. If such an approach were allowed, there could be a risk that movements lead to crest tension cracks which could then fill with water and unacceptably compromise stability. Given the consequences of a significant failure of such a high cut face in proximity to residential areas, it was decided that a displacement-based approach was not acceptable for the seismic cases for this project. For these reasons, a factor of safety of unity was targeted for the DCLS seismic case.

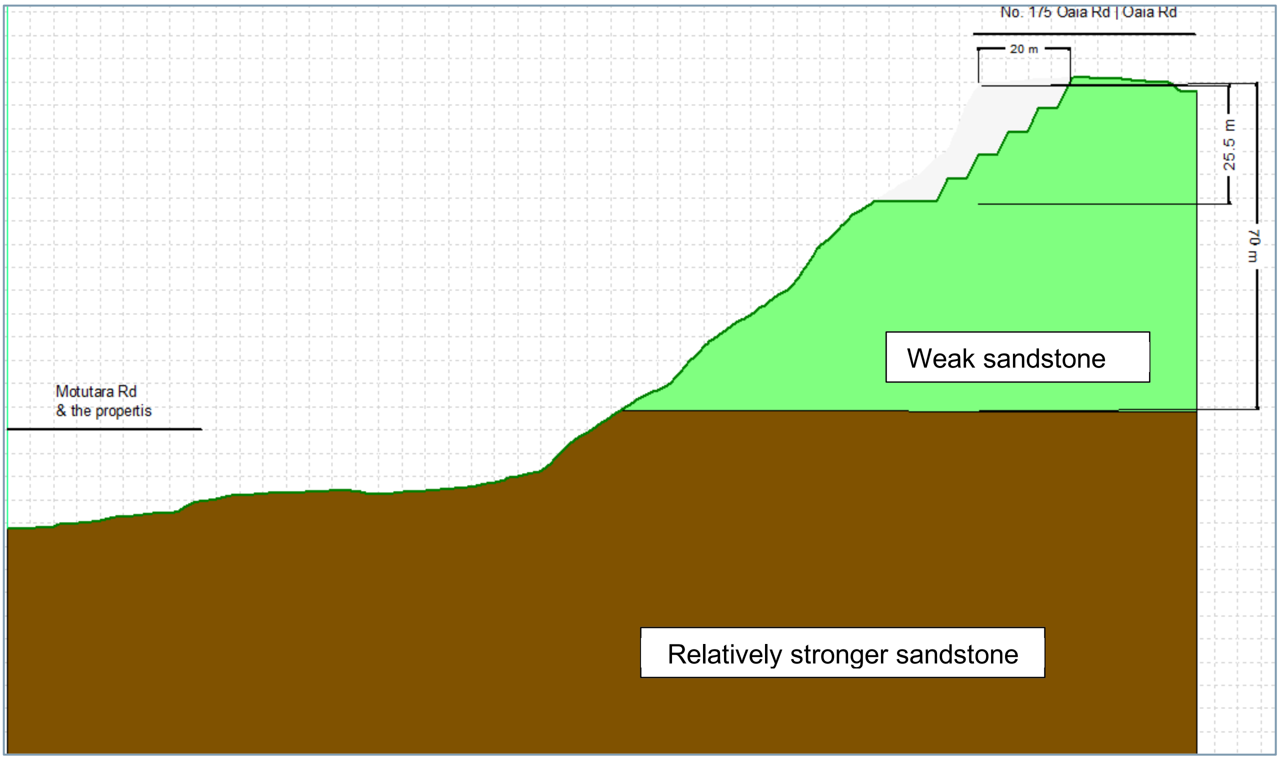


Figure C-8 Illustration of benching option

Construction of the benching option would need to include, but not be limited to, the following processes:

– Obtain any necessary easements if the benches were to extend over private property boundaries
– Preparation of a stable platform for plant
– Vegetation removal and/or trimming as required
– Apply erosion protection measures
– Consider suitable drainage system
– Top-down excavation processes

C5.4 Mitigation Cost Consideration and Cost Indication

Construction considerations of the two remedial options are included in Table C-6 to highlight the challenges with both options.

Costs associated with remediation is not possible without a more advanced design, paired with a detailed methodology. No consideration has been given to legal or consenting costs of either option.

We propose the following nominal order of magnitude constructed costs for either option:

- **Several hundred thousand dollars** per lineal metre of remediated slope.
- **Millions of dollars to repair damage** to existing February 2023 slips.
- **Tens of millions of dollars** to include the slope that did not experience landslide.

Table C-6 Remedial option construction consideration comparison (more X symbols equals less desirable)

Construction Consideration	Soil Nails		Benched Profile	
Site access (considers plant size and truck movements)	XX	Smaller plant	XXXXX	Large trucks. Damage to local roads from heavy truck movement.
Duration (machinery efficiency)	XXXXX	Smaller plant and hand work	XXX	Large machinery
Machinery size	X	Small rigs	XXXXX	Large trucks
Environmental (dust and erosion)	X	Drilling dust	XXXXX	Large exposed area
Environmental (noise)	XXXX	Loud drilling	XXXX	Loud large machinery
Safety risk to contractors	XXX	Many hours working at height on abseil	XXX	Fall from slope edge
Earthworks soil disposal	X	No disposal	XXXXX	Off site disposal
Change to existing slope profile	X	Strengthens in situ slope	XXXXX	Requires removal of slope, including buildings and infrastructure to the east of Muriwai. Requires bespoke stormwater design and infrastructure.
Post construction maintenance	XXXXX	Regular and expensive maintenance	XX	Minor earthworks and ongoing control of stormwater

C6. Limitations

This report has been prepared by GHD Limited (GHD) for Auckland Council and may only be used and relied on by Auckland Council for the purpose agreed between GHD and Auckland Council as set out in Section 1 of this report.

GHD otherwise disclaims responsibility to any person other than Auckland Council arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

The opinions, conclusions and any recommendations in this report are based on assumptions made by GHD described in this report (refer Section 1 of this report). GHD disclaims liability arising from any of the assumptions being incorrect.

GHD does not accept responsibility arising from, or in connection with, varied conditions and any change in conditions. GHD is also not responsible for updating this report if the conditions change.

An understanding of the geotechnical site conditions depends on the integration of many pieces of information, some regional, some site specific, some structure specific and some experienced based. Hence this report should not be altered, amended, abbreviated, or issued in part in any way without prior written approval by GHD. GHD does not accept liability in connection with the issuing of an unapproved or modified version of this report.

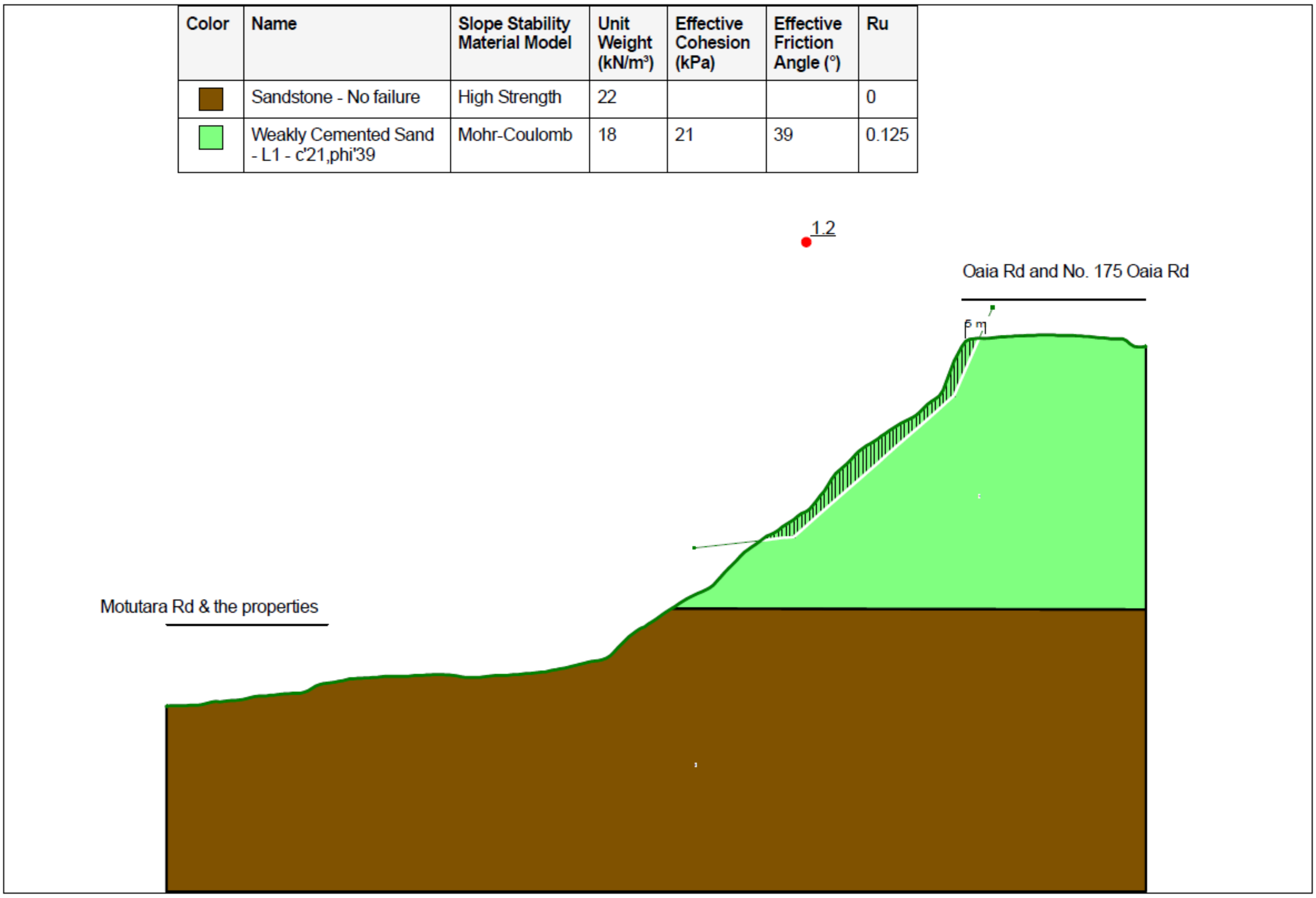
Verification of the geotechnical assumptions and/or model is an integral part of the design process - investigation, construction verification, and performance monitoring. If the revealed ground or groundwater conditions vary from those assumed or described in this report the matter should be referred back to GHD.

C7. References

- Edbrooke, S.W. (compiler), 2001. Geology of the Auckland Area. Institute of Geological and Nuclear Sciences 1:250,000 Geological Map 3. Institute of Geological and Nuclear Sciences Ltd, Lower Hutt.
- New Zealand Transport Agency (NZTA), Bridge Manual (SP/M/022) (Third edition, Amendment 4).
- Collins, B. D., & Sitar, N. (2009). Geotechnical properties of cemented sands in steep slopes. *Journal of geotechnical and geoenvironmental engineering*, *135*(10), 1359-1366.
- Federal Highway Administration (FHWA), (2015). Soil nail walls reference manual (FHWA-NHI-14-007). Washington, DC: FHWA.
- Auckland Council (2023). The Auckland Code of Practice for Lad Development and Subdivision (Version 2.0) (Chapter 2).
- MBIE and NZGS (2021). “Geotechnical Earthquake Engineering Practice: Module 1 – Overview of the Guidelines”. Ministry of Business, Innovation and Employment (MBIE) and New Zealand Geotechnical Society (NZGS).

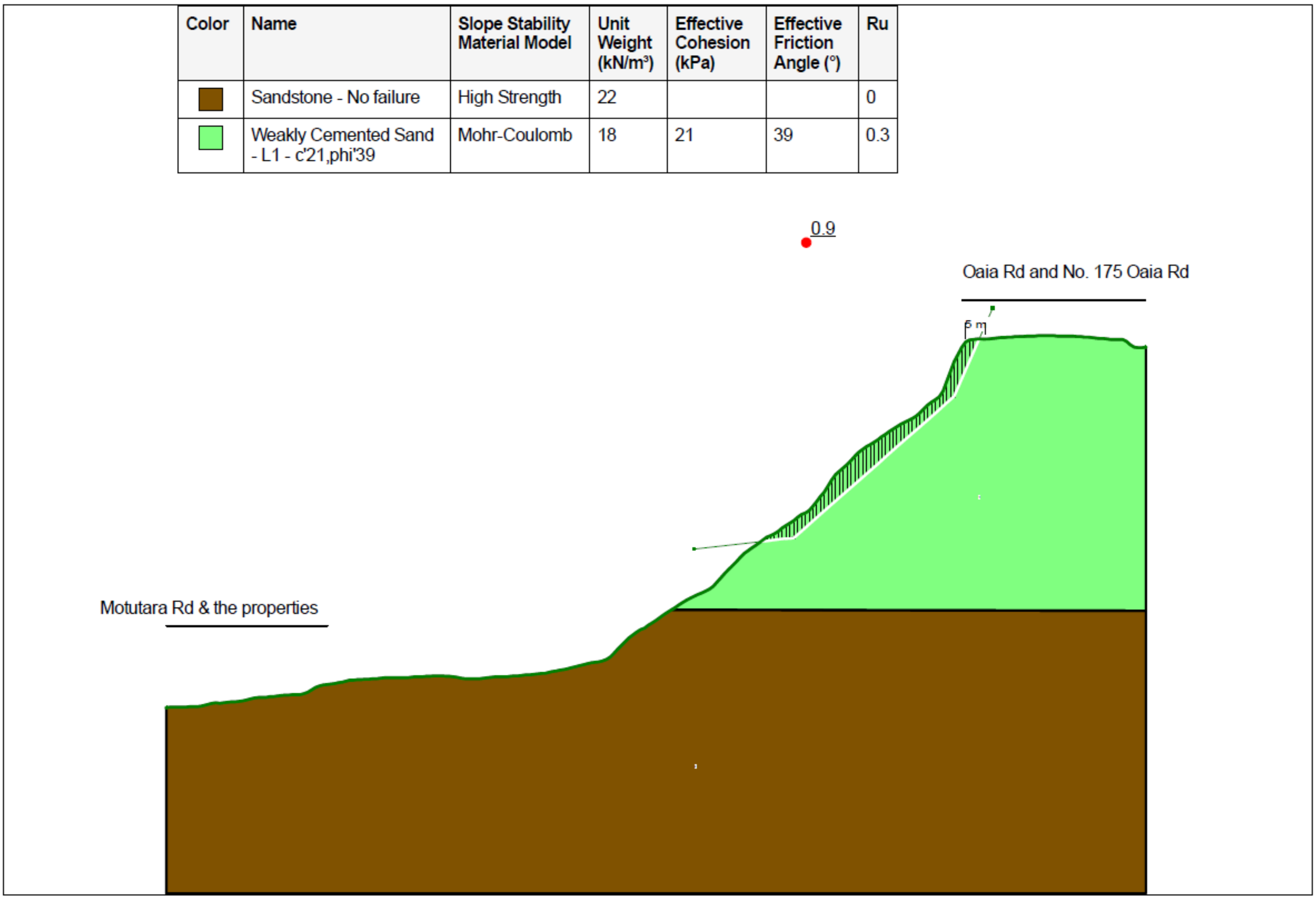
Appendix

Slope stability analysis output figures



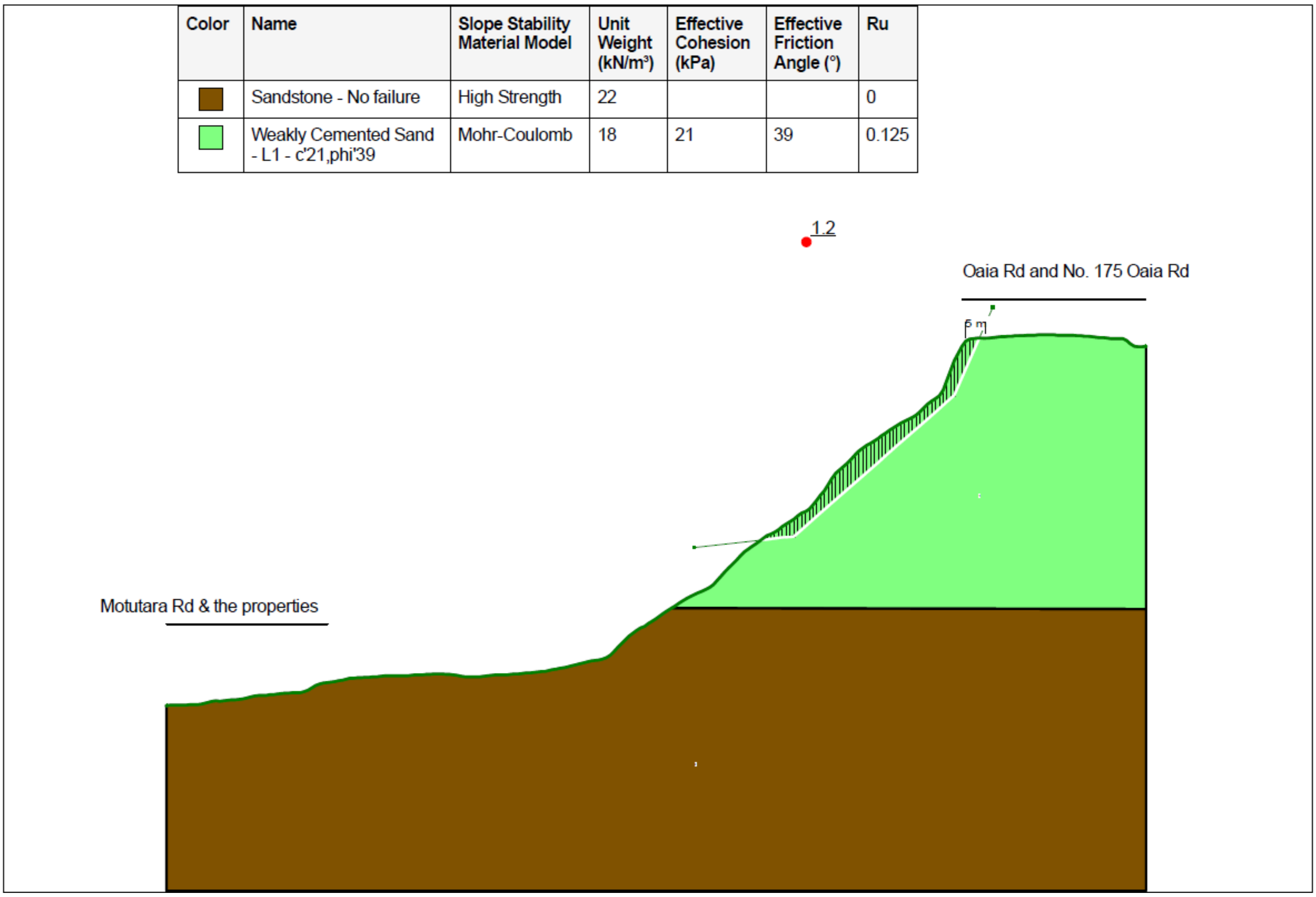
Color	Name	Slope Stability Material Model	Unit Weight (kN/m³)	Effective Cohesion (kPa)	Effective Friction Angle (°)	Ru
🟫	Sandstone - No failure	High Strength	22			0
🟩	Weakly Cemented Sand - L1 - c'21,phi'39	Mohr-Coulomb	18	21	39	0.125

Figure C(A)-1. Back Analysis - Normal Groundwater



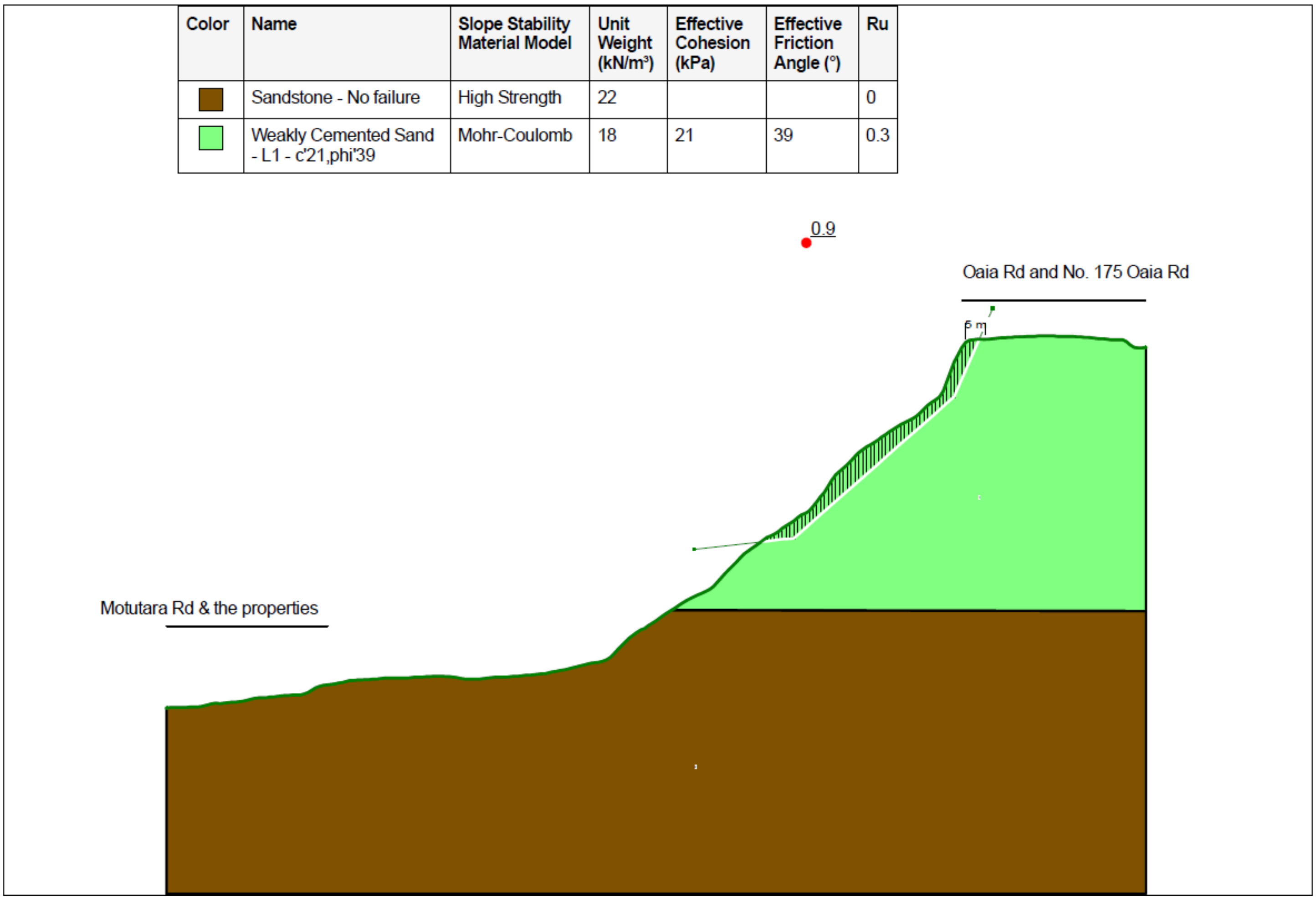
Color	Name	Slope Stability Material Model	Unit Weight (kN/m³)	Effective Cohesion (kPa)	Effective Friction Angle (°)	Ru
🟫	Sandstone - No failure	High Strength	22			0
🟩	Weakly Cemented Sand - L1 - c'21,phi'39	Mohr-Coulomb	18	21	39	0.3

Figure C(A)-2. Back Analysis - Extreme Groundwater



Color	Name	Slope Stability Material Model	Unit Weight (kN/m³)	Effective Cohesion (kPa)	Effective Friction Angle (°)	Ru
🟫	Sandstone - No failure	High Strength	22			0
🟩	Weakly Cemented Sand - L1 - c'21,phi'39	Mohr-Coulomb	18	21	39	0.125

Figure C(A)-3. Nail Option - Normal Groundwater



Color	Name	Slope Stability Material Model	Unit Weight (kN/m³)	Effective Cohesion (kPa)	Effective Friction Angle (°)	Ru
🟫	Sandstone - No failure	High Strength	22			0
🟩	Weakly Cemented Sand - L1 - c'21,phi'39	Mohr-Coulomb	18	21	39	0.3

Figure C(A)-4. Nail Option - Extreme Groundwater

Color	Name	Slope Stability Material Model	Unit Weight (kN/m³)	Effective Cohesion (kPa)	Effective Friction Angle (°)	Ru
🟫	Sandstone - No failure	High Strength	22			0
🟩	Weakly Cemented Sand - L1 - c'21,phi'39	Mohr-Coulomb	18	21	39	0.1

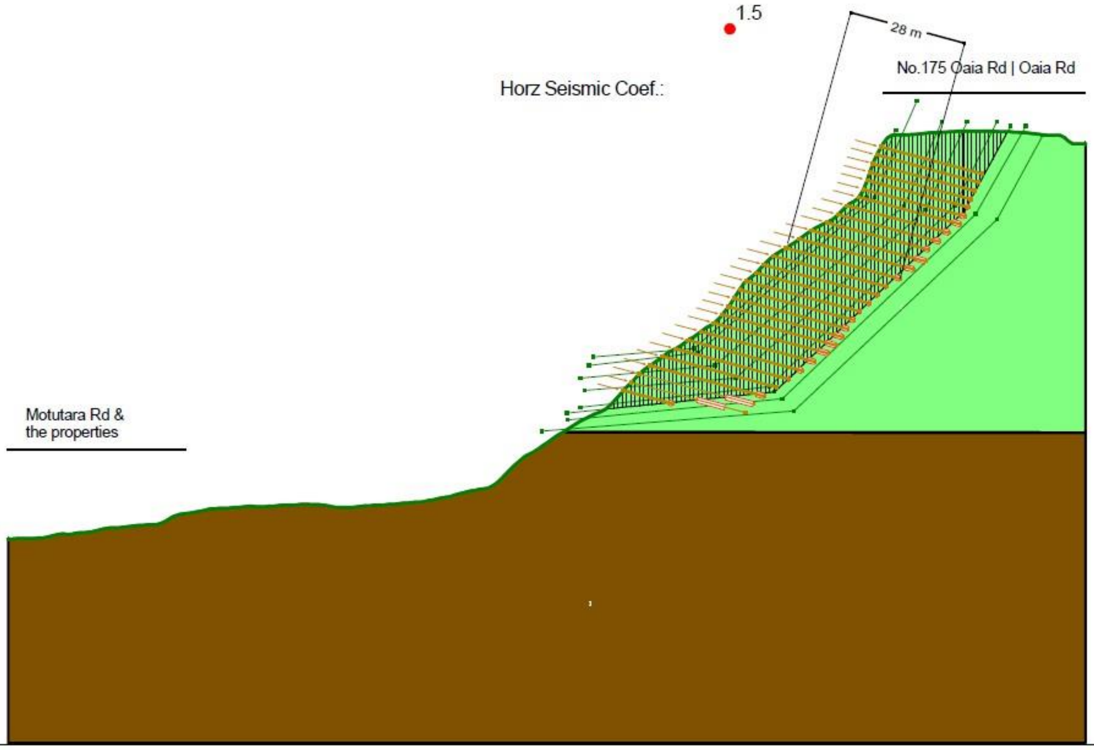


Figure C(A)-5. Nail Option - Nail Length (Static Case)

Color	Name	Slope Stability Material Model	Unit Weight (kN/m³)	Effective Cohesion (kPa)	Effective Friction Angle (°)	Ru
🟫	Sandstone - No failure	High Strength	22			0
🟩	Weakly Cemented Sand - L1 - c'21,phi'39	Mohr-Coulomb	18	21	39	0.1

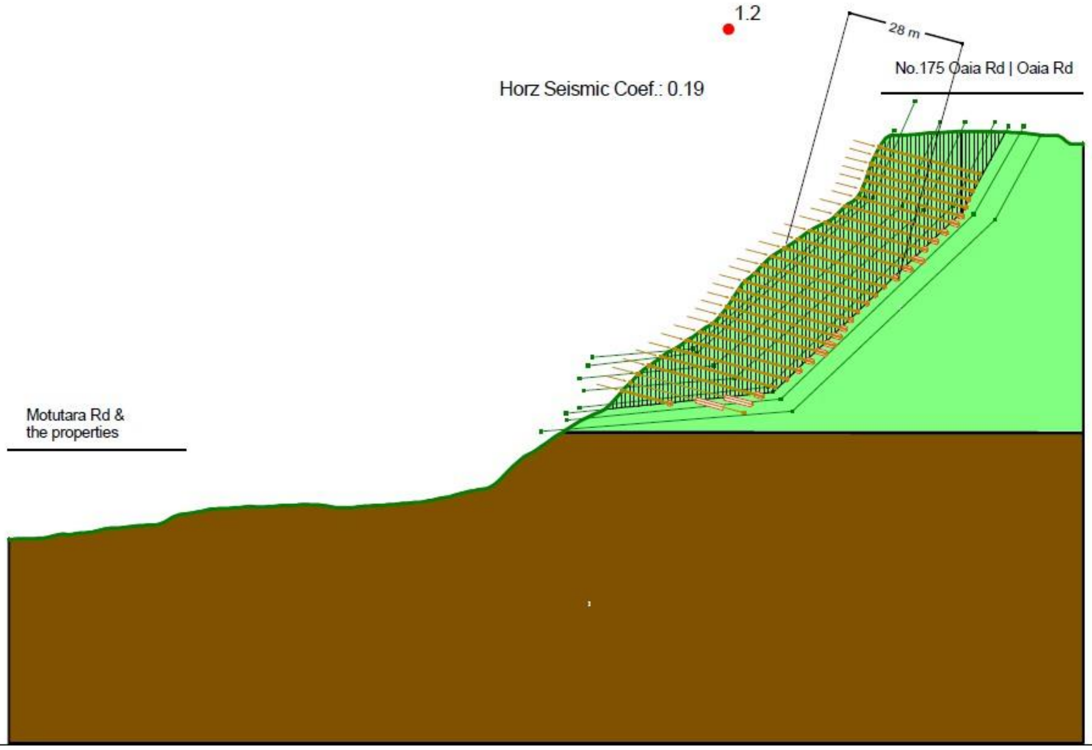
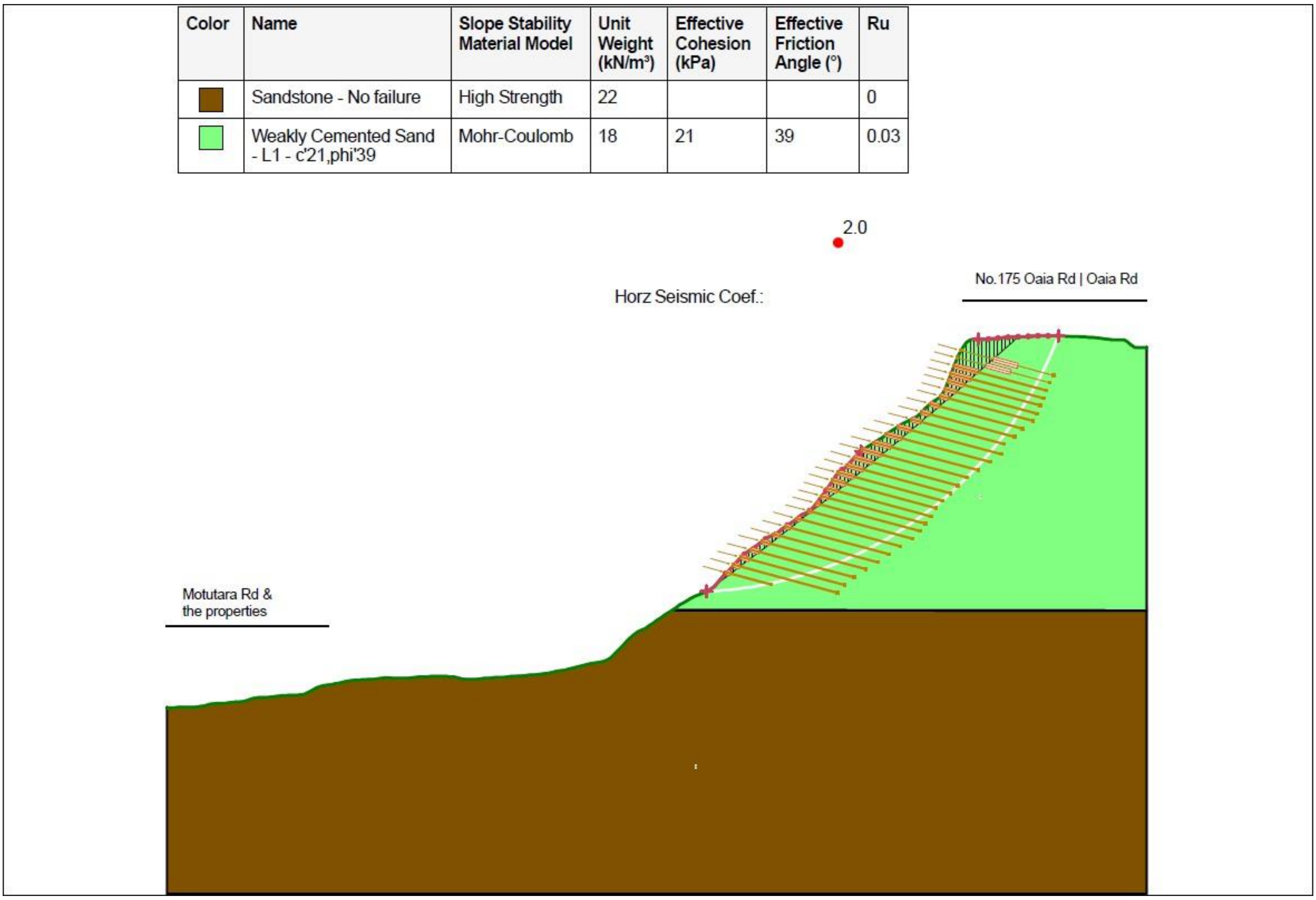
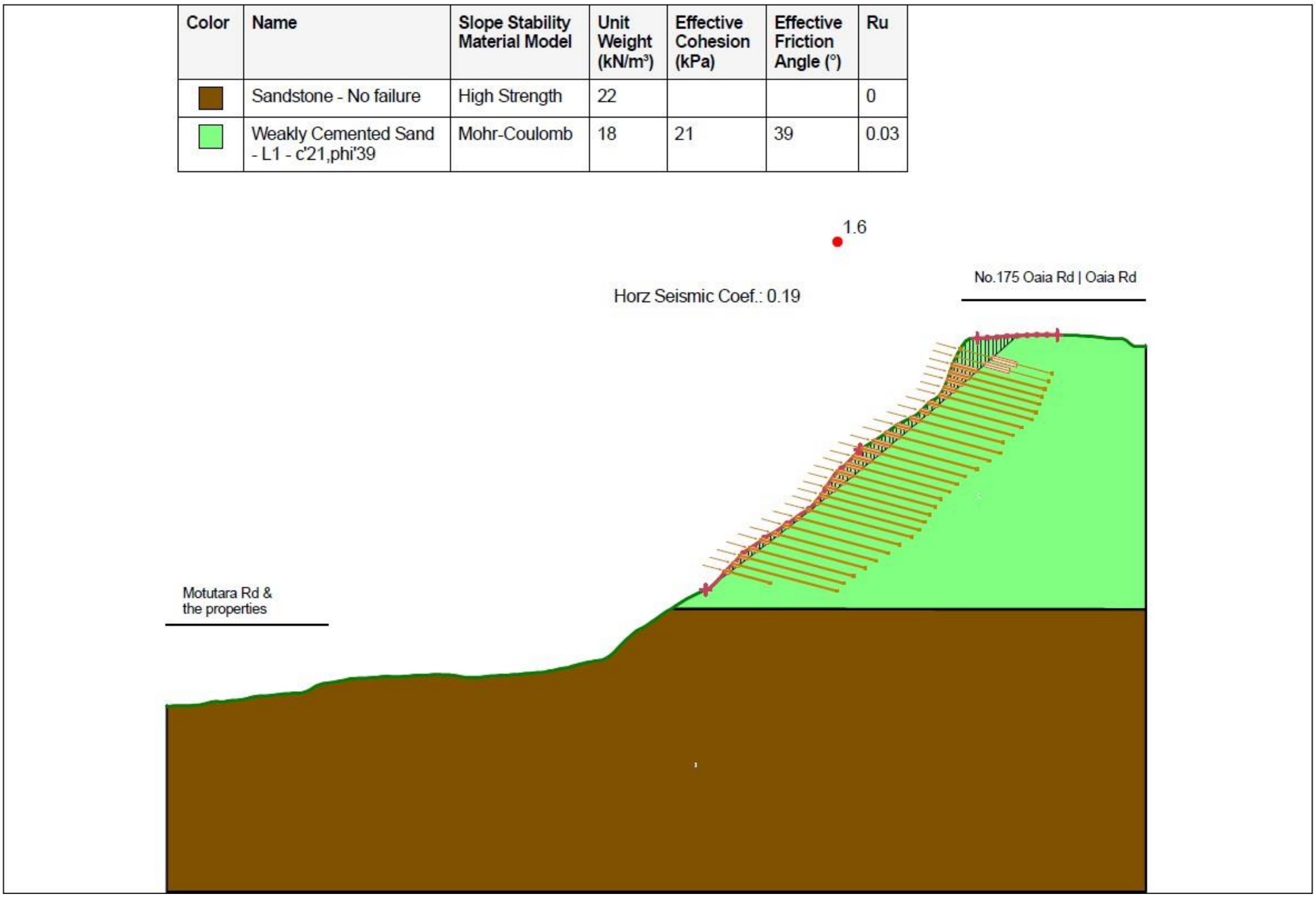


Figure C(A)-6. Nail Option - Nail Length (Seismic Case)



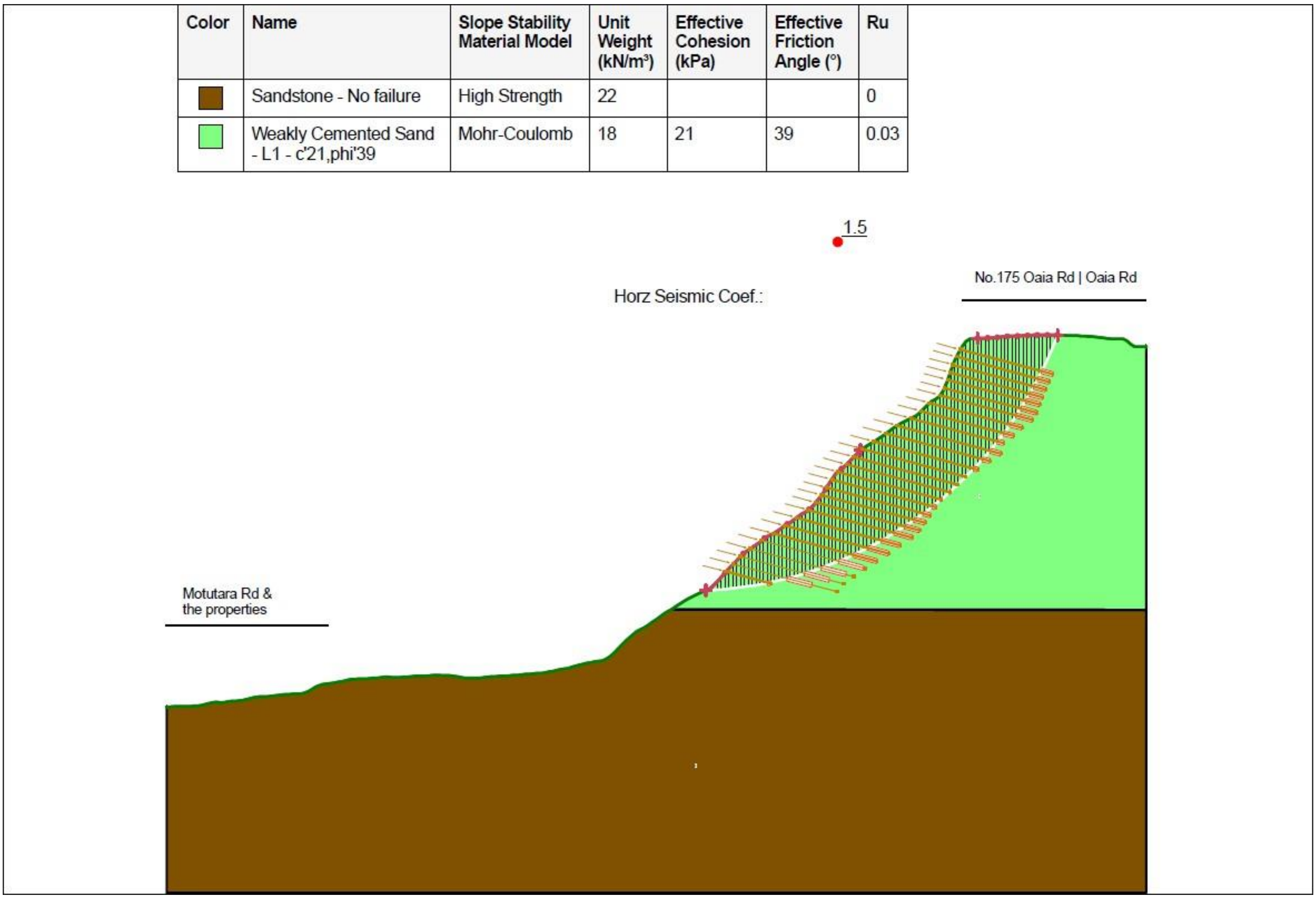
Color	Name	Slope Stability Material Model	Unit Weight (kN/m³)	Effective Cohesion (kPa)	Effective Friction Angle (°)	Ru
🟫	Sandstone - No failure	High Strength	22			0
🟩	Weakly Cemented Sand - L1 - c'21,phi'39	Mohr-Coulomb	18	21	39	0.03

Figure C(A)-7. Nail Option - Shallow Failure Surface (Static Case)



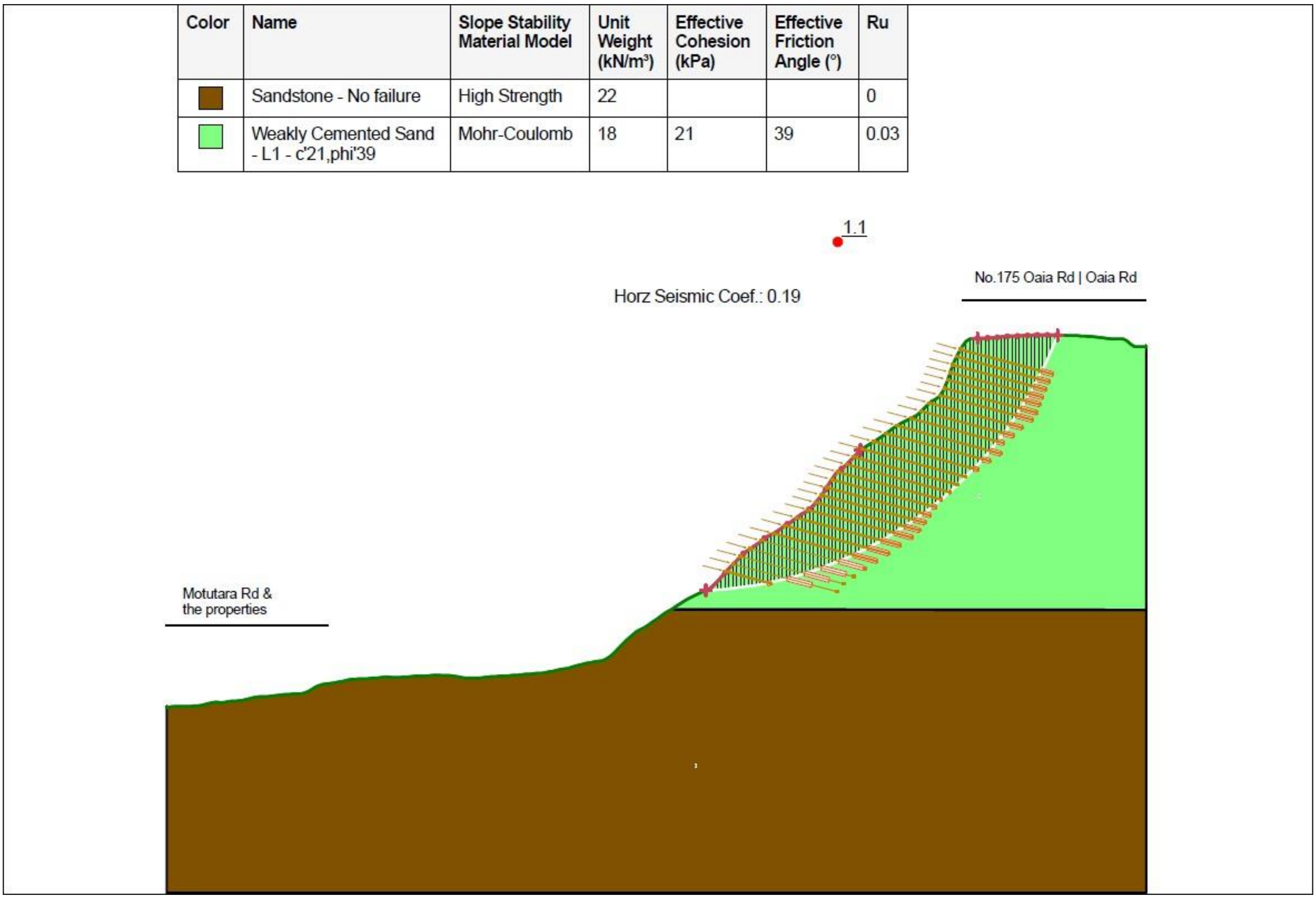
Color	Name	Slope Stability Material Model	Unit Weight (kN/m³)	Effective Cohesion (kPa)	Effective Friction Angle (°)	Ru
🟫	Sandstone - No failure	High Strength	22			0
🟩	Weakly Cemented Sand - L1 - c'21,phi'39	Mohr-Coulomb	18	21	39	0.03

Figure C(A)-8. Nail Option - Shallow Failure Surface (Seismic Case)



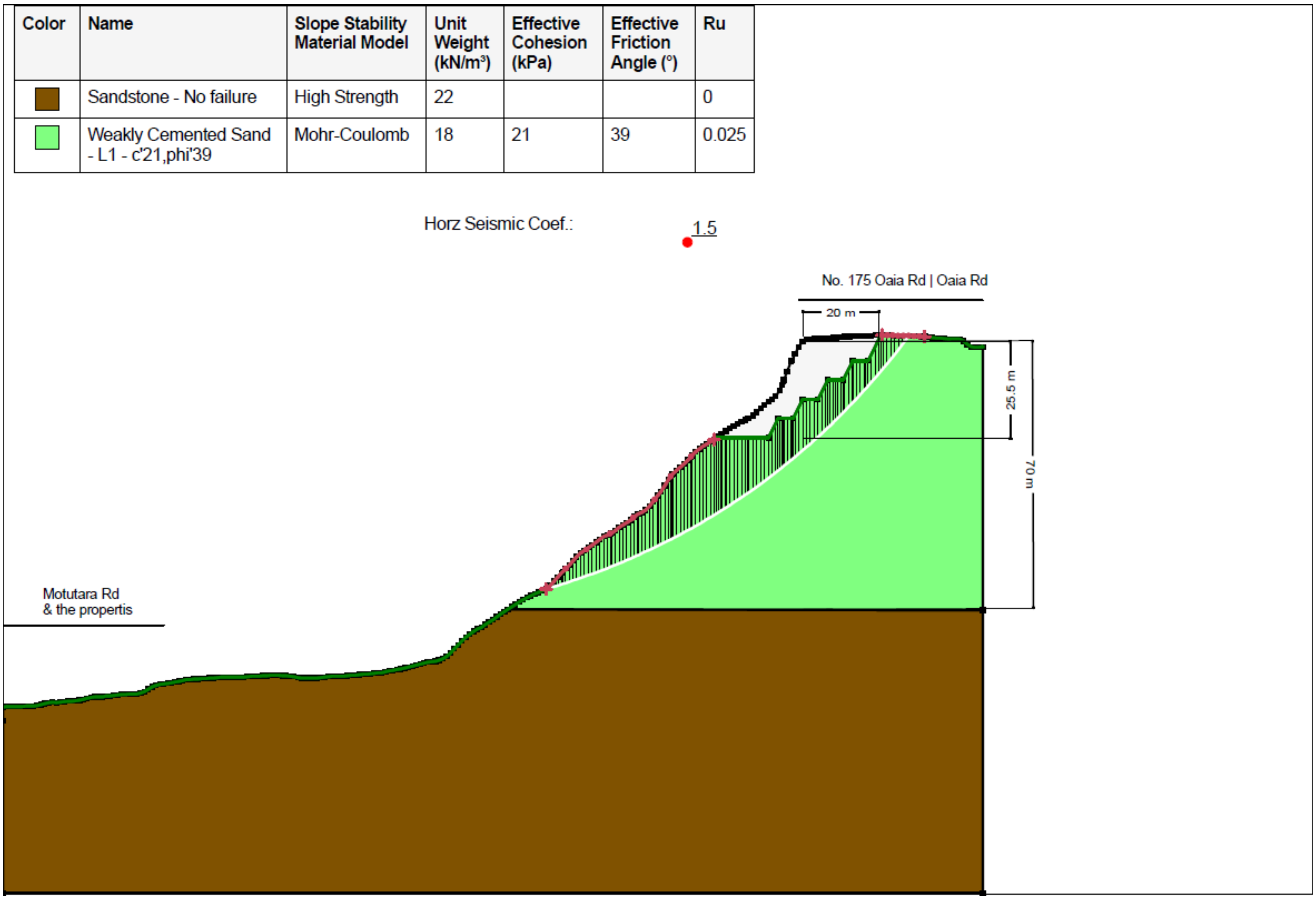
Color	Name	Slope Stability Material Model	Unit Weight (kN/m³)	Effective Cohesion (kPa)	Effective Friction Angle (°)	Ru
🟫	Sandstone - No failure	High Strength	22			0
🟩	Weakly Cemented Sand - L1 - c'21,phi'39	Mohr-Coulomb	18	21	39	0.03

Figure C(A)-9. Nail Option - Deep Failure Surface (Static Case)



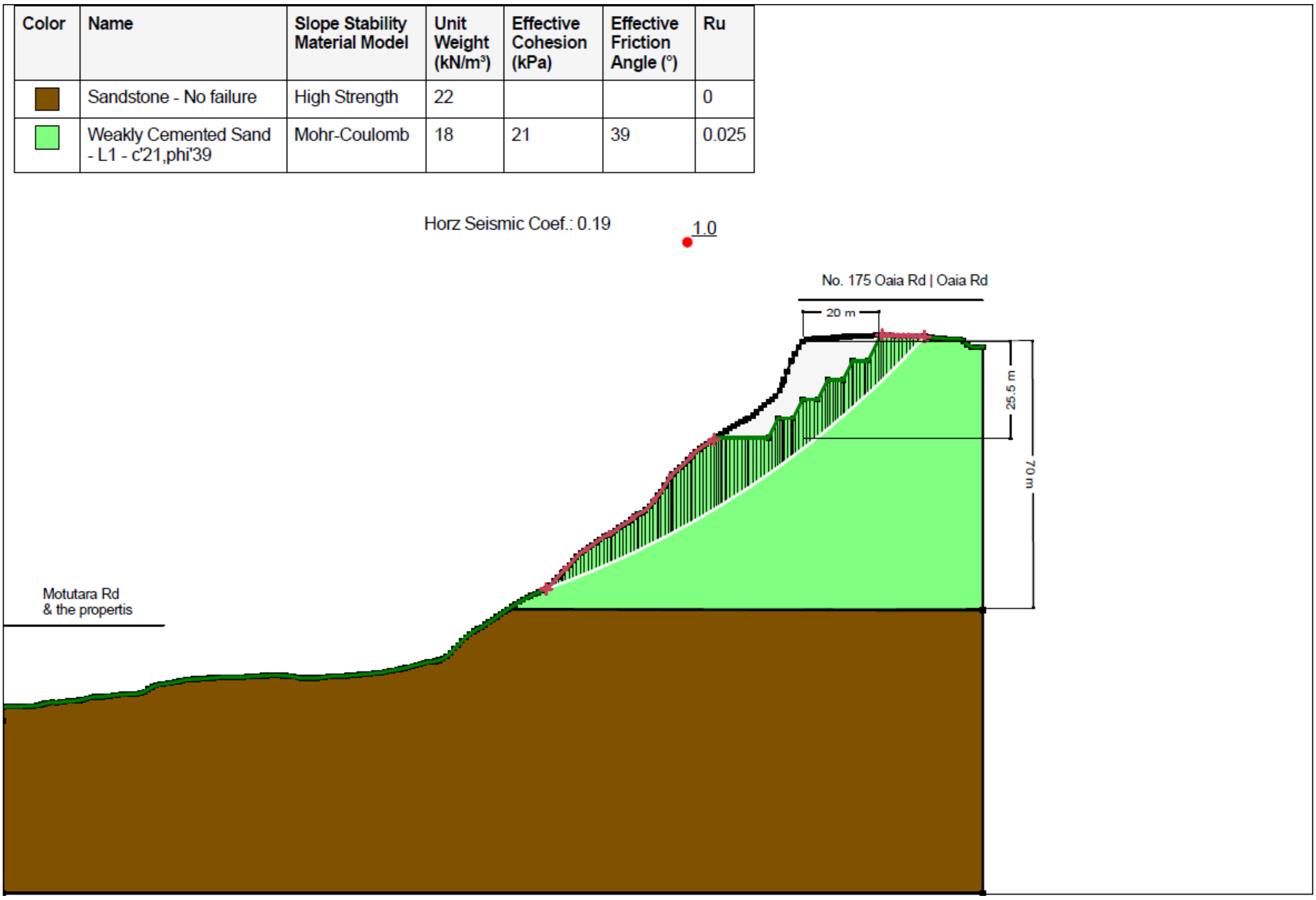
Color	Name	Slope Stability Material Model	Unit Weight (kN/m³)	Effective Cohesion (kPa)	Effective Friction Angle (°)	Ru
🟫	Sandstone - No failure	High Strength	22			0
🟩	Weakly Cemented Sand - L1 - c'21,phi'39	Mohr-Coulomb	18	21	39	0.03

Figure C(A)-10. Nail Option - Deep Failure Surface (Seismic Case)



Color	Name	Slope Stability Material Model	Unit Weight (kN/m³)	Effective Cohesion (kPa)	Effective Friction Angle (°)	Ru
🟫	Sandstone - No failure	High Strength	22			0
🟩	Weakly Cemented Sand - L1 - c'21,phi'39	Mohr-Coulomb	18	21	39	0.025

Figure C(A)-11. Bench Option - Static Case



Color	Name	Slope Stability Material Model	Unit Weight (kN/m³)	Effective Cohesion (kPa)	Effective Friction Angle (°)	Ru
🟫	Sandstone - No failure	High Strength	22			0
🟩	Weakly Cemented Sand - L1 - c'21,phi'39	Mohr-Coulomb	18	21	39	0.025

Figure C(A)-12. Bench Option - Seismic Case

ghd.com

→ The Power of Commitment

Appendix D

RAMMS Debris Flow Analysis

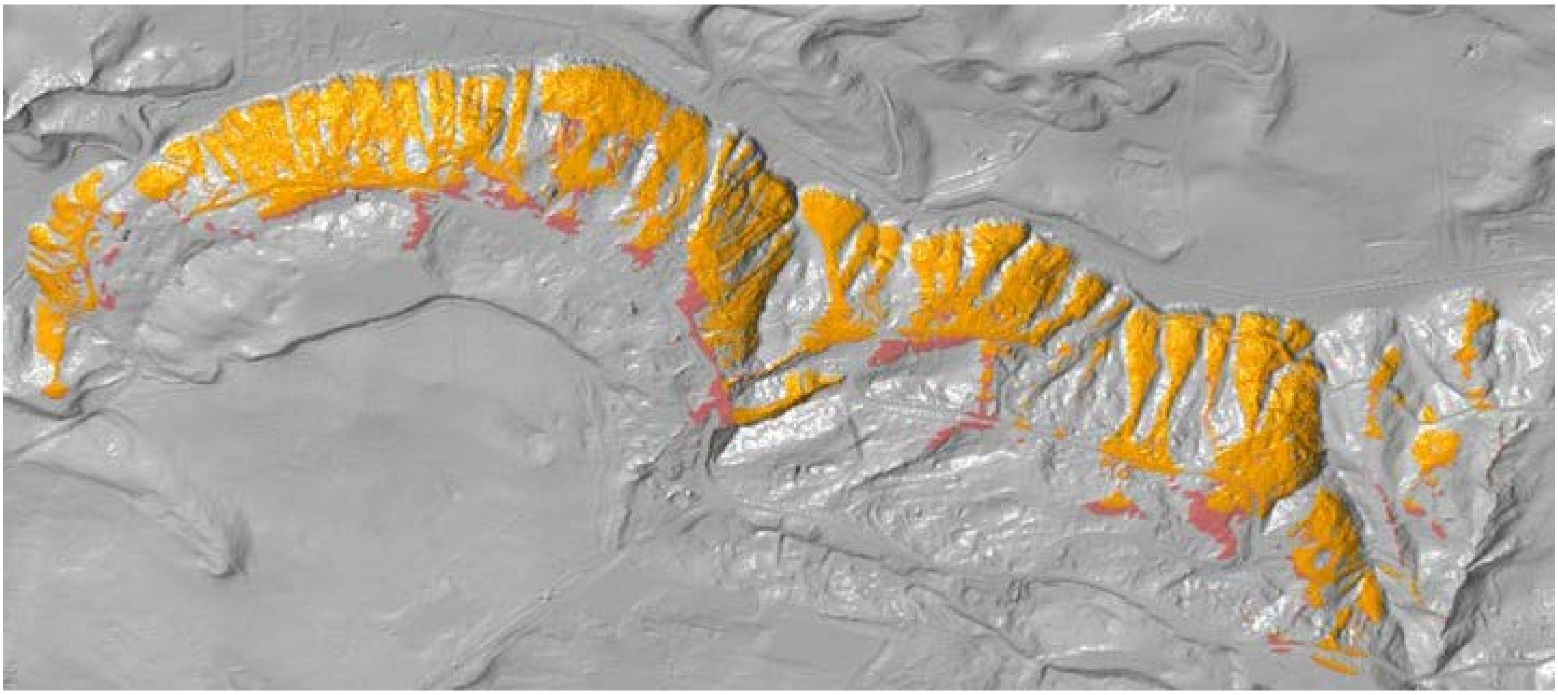
Waitakere Coastal Communities Landslide Risk Assessment

Appendix D – Muriwai RAMMS debris flow analysis report

Auckland Council

15 May 2024

→ The Power of Commitment



Project name	Waitakere Coastal Communities Landslide Risk Assessment
Document title	Waitakere Coastal Communities Landslide Risk Assessment | Appendix D – Muriwai RAMMS debris flow analysis report
Project number	12612462
File name	12612462_Appendix D RAMMS_FINALRev2.docx

Status Code	**Revision**	**Author**	**Reviewer**		**Approved for issue**		
			Name	**Signature**	**Name**	**Signature**	**Date**
S4	0	Matt Howard	Don Macfarlane	D Macfarlane	Roy Pearson	Roy Pearson	03/11/2023
S4	1	Matt Howard	Don Macfarlane	D Macfarlane	Roy Pearson	Roy Pearson	30/04/2024
S4	2	Matt Howard	Don Macfarlane	D Macfarlane	Roy Pearson	Roy Pearson	15/05/2024
[Status code]							
[Status code]							

GHD Limited
Contact: Matt Howard, Technical Director - Engineering Geologist | GHD
27 Napier Street, GHD Centre Level 3
Freemans Bay, Auckland 1010, New Zealand
T +64 9 370 8000 | **F** +64 9 370 8001 | **E** aklmail@ghd.com | **ghd.com**

The Power of Commitment

Contents

Table index

Figure index

Appendices

D1. Introduction

D1.1 Purpose of this report

GHD has been engaged by Auckland Council (AC)[1] to carry out landslide risk assessments as well as to provide associated landslide risk management advice and geotechnical investigations in the Waitakere area, specifically for the residential areas of Muriwai, Piha and Karekare.

The purpose of this assessment is to present the results of a RAMMS computer-simulated three-dimensional debris flow assessment undertaken to provide guidance on the potential effects of future events on dwellings in Muriwai. In addition, a sensitivity analysis of input parameters is presented. The analysis focus is on the large-scale hazard from the 80 m-high escarpment to the east of Muriwai township that experienced damaging landslides in February 2023. The results from the analysis provide an important part of the GHD loss of life risk study (see Appendix E of the overall report) that will support decision-making by AC on the long-term suitability of sites and dwellings for occupancy.

This report is an appendix to the overall GHD landslide risk report and should be read in conjunction with it, as well as associated appendices. The covering report contains additional background information and the results of other assessments carried out by GHD that are not included herein.

D1.2 Background

Two significant rainfall events affected the Waitakere area in late January and early February, resulting from the impacts of ex-tropical cyclones Hale and Gabrielle, respectively.

The Cyclone Gabrielle weather event of 14 February 2023 resulted in widespread catastrophic flooding and slope instability in the settlement of Muriwai where several debris avalanches (which included rocks and trees) occurred, some of which turned into saturated debris flows as they travelled downslope. These flows resulted in damage to buildings and infrastructure. Two fatalities occurred due to impact of landslides on private dwellings. This tragic event was similar to a 1965 storm event that also claimed two lives.

Following the event, rapid building assessment of residential properties was undertaken in Muriwai, with some houses having access by owners restricted (a yellow placard – e.g. access in daylight hours only) and some for which no access was permitted (a red placard).

The modelling of potential debris flows was identified as an important element of understanding the ongoing future risk to the Muriwai community.

D1.3 Scope

The scope for this work is as follows:

- Establish a ground surface model using data provided by AC.
- Calibrate RAMMS input parameters to replicate the observed runout distance of February 2023 debris flows.
- Identify areas of the escarpment that could be susceptible to future landslides in rare, large rainfall events
- Using RAMMS, simulate the failure of future landslide source areas leading to large-scale, destructive landslides.
- Conduct a RAMMS analysis specifically for Geomorphological Zone 5, which is located at the southern end of Muriwai between Domain Crescent and Waitea Road.
- Provide a plan of the area potentially affected by debris flows of sufficient thickness that could cause loss of life (i.e. greater than 0.5 m).

---

[1] Under Contract CW198379, Master Services Agreement CCCS: CW74240 dated 7/09/2019

AC requested that this study be limited to the assessment of the effect from 'large scale[2]' landslide hazards originating from the main escarpment located to the south-east of Muriwai because the initial placard assessment was largely aimed at mitigating risks associated with these landslide hazards. Consequently, this report does not consider smaller, more localised landslide hazards that could originate (or may have already initiated) from other areas in Muriwai such as within the footprint of individual residential properties. The exception to this is 3 specific property's (85 and 87 Domain Crescent and 207 Motutara Road). The basis for this is outlined in Section 1.3 (footnote 3) of the Overall Report.

This report has been prepared by GHD for Auckland Council and may only be used and relied on by Auckland Council for the purpose agreed between GHD and Auckland Council as set out in section 1.1 of this report.

GHD otherwise disclaims responsibility to any person other than Auckland Council arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

D1.4 Report structure

The accompanying GHD Engineering Geology report provides a detailed description of the site as well as discussion of site geology and geomorphology, historical landsliding, landslide mapping, landslide classification and slope processes. The reader is advised to consult the accompanying GHD reports for further information not contained herein. A list of report sections is presented in Table D1. A3 plans referred to in this report are listed in Table D2 and RAMMS output figures are presented in Appendix D-1.

Table D1 Summary of accompanying Muriwai landslide risk assessment reports

Report Section	Description
Overall Report	Waitakere Coastal Communities Landslide Risk Assessment (Muriwai)
Appendix A	Figures
Appendix B	Engineering Geological Report
Appendix C	Slope Stability Assessment
Appendix D	*RAMMS debris flow analysis (this report)*
Appendix E	Landslide Risk Assessment
Appendix F	Geotechnical Investigations Report

Table D2 List of RAMMS debris flow simulation plans in Appendix A that are associated with this report

A201	Maximum debris height extents for best case, predicted and worst case scenarios -(greater than 0.01 m deep) - overview
A202	Predicted maximum debris height (greater than 0.01 m deep) - overview
A203 – A205	Predicted maximum debris height (greater than 0.01 m deep) - close-up
A206	Maximum debris height extents (greater than 0.5 m deep) - overview
A207 – A209	Maximum debris height extents (greater than 0.5 m deep) - close-up

---

[2] In this report 'large scale' landslide hazards refers to landslides originating from the main escarpment that typically have a volume of more than about 50 m^3 with the potential to cause total or partial collapse of a dwelling.

D2. RAMMS Debris Flow Modelling

D2.1 Description of software

The RAMMS Debris flow module (RAMMS) is a three-dimensional numerical software package developed by the WSL Institute for Snow and Avalanche Research and is used to simulate the runout of debris-laden flows in complex terrain. Version 1.8.0 was used for this analysis.

RAMMS is a credible modelling tool that is frequently used in New Zealand and internationally. Like most similar modelling techniques, RAMMS is a simplification of a process that is inherently complex and unpredictable. Consideration of observed landslide behaviour is essential to obtain credible results.

The extent of simulated debris flows can be presented as ‘heat maps’ of depth, maximum depth, maximum velocity or maximum pressure. We have attributed the vulnerability metric of maximum depth in the risk analysis (see Appendix E of the overall report) as being the most relevant to understanding the potential hazard to occupants of dwellings. RAMMS outputs are therefore presented as maximum depth and the modelled landslide runout zones are referred to in this report as the ‘Predicted modelled debris runout zone’.

D2.2 Ground surface model

RAMMS uses a surface ‘digital elevation’ model (DEM) as the base layer for its calculations. It is important to have a representative surface model that accurately depicts slopes, ridges and channels, all of which influence the path of debris flows. Surface models that are insufficiently detailed may give overly conservative results, as the software perceives unrealistically smooth terrain. The RAMMS (2022)[3] guidance document is not definitive on the minimum spacing, but our experience is that a surface model should have points at or closer than 1 m.

We obtained data from AC and publicly available sources. The surface model used included the following:

- LiDAR surface data (1 m point spacing) and aerial imagery (0.15 m resolution) obtained 2016-2018 (provided by AC)
- LiDAR surface data (1 m point spacing) and aerial imagery (0.15 m resolution) obtained 2023 (provided by AC) following Cyclone Gabrielle
- Mapped landslide extents recorded remotely and from GHD 2023 field mapping (see the Engineering Geology Report – Appendix B of the overall report)

Surface data is processed to remove vegetation and dwellings.

Our RAMMS simulation considers whether a pre or post February 2023 DEM is appropriate. The pre 2023 event DEM was used to calibrate existing landslides and the post event DEM was used to model future debris flows as the terrain has been altered by recent debris deposition. Comparison of the elevation of the two DEMs has identified that there is a difference between each model of 0.3 m, which may reflect the accuracy of one or both of the models. This is discussed in more detail in section B3.1.1 of the Engineering Geology Report – Appendix B of the overall report.

D2.3 Input parameter options

Debris flows involve a dynamic interaction of flowing material that is part liquid and part solid. As the mass descends the slope this ratio constantly changes, resulting in complex dynamics within the flow and between the flow and ground. To simulate this, RAMMS uses some input parameters that are described in detail in the supplier user manual (RAMMS, 2022).

The following describes the RAMMS parameters that can be varied:

---

[3] RAMMS (2022). RAMMS: DEBRISFLOW User Manual v.8.0. Davos, Switzerland: ETH

Hydrograph and block release

Debris flows are often associated with large, basin-shaped catchments where debris is entrained within floodwaters in a river channel and discharged at the top of a fan ‘apex’. A hydrograph can be used as an input to describe the expected flow over time, which is often developed for a particular catchment. This influences the discharge and duration of debris flow.

Block release is where a thickness of debris for a defined area is released. Block release can be applied to multiple areas per simulation. The initial February 2023 landslides are interpreted as being a solid detachment of weakly cemented sandstone that liquefied during descent. RAMMS does not specifically model this scenario – this is accounted for in the calibration of the input parameters.

Debris flow material properties

- Frictional parameter Mu (μ), which is unitless. It is a measure the basal friction – the friction that occurs during interaction between the surface of the flow and the ground surface below. Landslides with higher Mu values result in shorter and more narrow runouts. RAMMS (2022) suggests a starting Mu value of approximately 0.2, with 0.05 - 0.4 providing realistic results values. Outside this range is not recommended, with Mu of zero giving visco-plastic behaviour and greater than 0.4 seldom producing useful simulation results.
- Frictional parameter Xi (ξ), in units of m/s^2. This represents the viscous-turbulent properties of the landslide slurry. Higher Xi values indicate more laminar flows that travel further. RAMMS (2022) recommends that Xi is between 100 and 200 m/s^2 for granular flow (solid-dominated).
- Flow density (ρ), in units of kg/m^3. Density represents the bulk density of solids and fluids within the flow. RAMMS (2022) recommends a value of 2000 kg/m^3 if details of the landslide are not available.

Stop Criteria

There are two ‘Stop Criteria’ that dictate when a simulation stops running in RAMMS. The simulation will stop at whichever criteria is fulfilled first. The purpose of this is to avoid misleading results due to the expansion of the debris mass at the end of the movement when most energy has been expended. The criteria are:

- The momentum-based ‘Percentage total momentum’ (energy cutoff). The default setting in RAMMS is 5%, i.e., when 95% of the mass has stopped. This can be adjusted to account for faster or slower mass movement speeds. The RAMMS (2022) suggested range for reasonable results is between 1% and 10%. For a value that is too low, the debris flow will continue to creep at extremely low velocity (i.e. the simulation lasts too long) and for a too high value the simulation will terminate prematurely.
- The centre-of-mass based ‘Centre-of-mass velocity threshold’ (m/s). The default setting in RAMMS is 0.2 m/s, i.e., the model terminates when the centre of mass velocity is below this value. This value is useful for address slow, creeping mass movements, but is not appropriate where there is more than one landslide being activated simultaneously. For Muriwai a value of zero is appropriate.
- End Time (s) – This represents the amount of time the simulation will allow the landslide to flow for. It is desirable to have a simulation end due to the Stop Criteria of the landslide or due to low flow rates (‘low flux’). It is less desirable to have a ‘time end condition’, which indicates neither the target stopping criteria nor low flux condition has been met.

Erosion function

The erosion function predicts the depth of erosion of sediment caused by debris flows. This can be used to predict the increase in volume of a debris flow as it travels along a channel. The erosion parameters are: erosion density (of the landslide debris); erosion rate of material from the channel; potential erosion depth; the critical shear stress where erosion can occur, and; the maximum erosion depth. The disadvantage of incorporating erosion is that you cannot specify the release volume before the simulation starts as it is created as a function of the debris flow.

Filtering of depth results

The results of the RAMMS analysis can be filtered to show the depth range of interest. This can be done to remove the presence of thin, non-life-threatening debris at landslide margins.

Effect of vegetation and buildings

The influence of trees acting to impede or add to debris flow damage on February 2023 landslides has been observed. Similarly, buildings may alter the natural path of part or all of a debris flow. It is possible to apply an impassable zone to physically block a simulated debris flow, but predicting the behaviour of individual trees and buildings in an area-wide study is not possible and has not been applied.

D2.4 Model calibration and selected input parameters

2.4.1 Calibration purpose and input parameter selection

Calibration of a RAMMS model with actual debris flow observations is important to account for the unique material and terrain characteristics in a particular location. At the large escarpment south-east of Muriwai there are more than ten large (several tens of metres wide) landslide source areas, all in similar Awhitu Group weakly cemented sandstone (see Appendix B of the overall report for a description of the Engineering Geology). This provides a compelling dataset of landslides and associated debris runout to guide assumptions on future large slope failures on the escarpment. Aligning the RAMMS model with existing failures provides confidence in its application elsewhere on the escarpment.

We calibrated the RAMMS model against the February 2023 landslides shown in Figure D1 and Table D3. In addition, the following values were selected:

- ‘Block release’ of debris
- Stop Criteria:
  - The momentum-based ‘Percentage total momentum’ – 5% was selected. The process for making the selection is presented in Figure D6.
  - The centre-of-mass based ‘Centre-of-mass velocity threshold’ – 0 m/s was selected, which is appropriate for multiple release areas/catchments.
  - End time – this varied between simulations due to the parameters of the RAMMS calculation for the ‘predicted modelled’ scenario. All simulations had an end time of 180 seconds. These met the desirable condition of ‘low flux’.
- Erosion function – this was not used for calibration, as the concentrated channelised flow described in RAMMS (2022) is not observed at Muriwai, with more distributed flows being evident.
- Simulations have been filtered to show maximum depths of greater than 10 mm so that comparisons with actual landslide extents is possible.

The release areas were defined in RAMMS using the mapped source area extents and estimated depth. It was noted that some landslides comprise individual, large source areas, while others have numerous, smaller source areas, with debris combining further downslope. We used both of these configurations for our calibration to represent these cases. The 2016 surface DEM was used to best represent the ground conditions existing at the time of the recent landslides. All RAMMS output figures are presented in Appendix D-1 of this report.

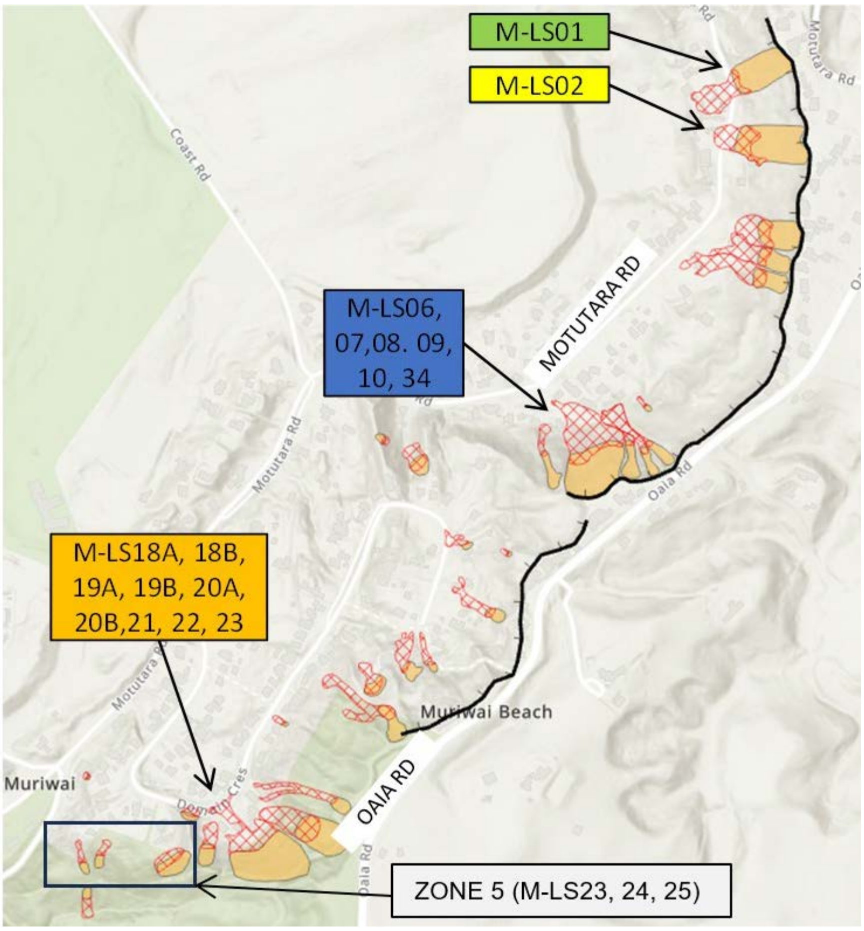


Figure D1 Location of landslides used for RAMMS calibration

Table D3 Landslides used to calibrate the RAMMS simulation. Shading is used to show groupings of landslides. Landslide ID is GHD-named (see Appendix B for full list of landslides).

Landslide ID No.	Release Area (m^2)	Average Release Thickness (m)	Released Volume (m^3)
M-LS01	2400	0.5	1220
M-LS02	1800	0.5	900
M-LS06	400	0.25	101
M-LS07	400	0.25	100
M-LS08	900	0.25	200
M-LS09	1900	0.75	1500
M-LS10	400	0.25	100
M-LS34	600	0.25	100
M-LS18A	200	0.25	50
M-LS18B	200	0.5	100
M-LS19A	800	0.25	200
M-LS19B	2000	0.25	500
M-LS20A	200	0.5	100
M-LS20B	3600	0.75	2700
M-LS21	500	0.25	100

Landslide ID No.	**Release Area (m^2)**	**Average Release Thickness (m)**	**Released Volume (m^3)**
M-LS22	200	0.25	50
M-LS23	700	0.5	400

Where parameters were recommended by RAMMS, these were initially applied and modified to obtain a runout extent that best matched what was observed. This was done by showing the mapped landslide extents beneath a transparent RAMMS overlay. The selected input parameters are presented in Table D4. Calibrated, best-fit output images are presented as Figure D2 to Figure D5.

Table D4 Selected input values for calibration (bold is conservative)

Parameter	Units	Typical Range (bold is conservative)	Range tested	Selected Value For Calibration
Density* (p)	kg/m^3	1800 - **2000**	-	2000
Basal Friction (Mu)	n/a	**0.1** - 0.4	**0.05** - 0.5	0.225
Viscous turbulent (Xi)	m/s^2	100 - **200**	**5 - 200**	87.5

Geomorphological Zone 5

The study area has been divided geomorphologically into six landslide ‘zones’ based on the surface topography, February 2023 landslide characteristics and general geomorphology. The purpose of this is to differentiate areas according to their susceptibility for large-scale landslides. The basis for the zoning and the zone characteristics are described in Section B5.3 of the Engineering Geology Report – Appendix B of the overall report.

There are similarities between Zone 5 and the main escarpment (i.e. Zone 2 to Zone 4), however, the source area is not as high, has different topography and may have groundwater conditions that are more favourable to slope stability. We assess this to mean that the potential extent of future debris flow in Zone 5 is better evaluated by having a specific RAMMS calibration for simulation purposes[4]. The landslides calibrated in Zone 5 were M-LS23, M-LS24 and M-LS25 (see Table D5). The release thickness for each landslide was adjusted with the RAMMS input values in Table D6 to best match observed landslide debris runout.

Table D5 Landslides used to calibrate the RAMMS simulation. Shading is used to show groupings of landslides. Landslide ID is GHD-named (see Appendix B for full list of landslides).

Landslide ID No.	**Release Area (m^2)**	**Average Release Thickness (m)**	**Released Volume (m^3)**
M-LS23	700	0.3	210
M-LS24	130	0.2	26
M-LS25	130	0.1	13

Table D6 Selected input values for calibration

Parameter	Units	Selected Value For Calibration
Density* (p)	kg/m^3	2000
Basal Friction (Mu)	n/a	0.4
Viscous turbulent (Xi)	m/s^2	500

---

[4] The Zone 5-specific information contained in this report have been previously documented in a letter to AC on 6 December, titled Muriwai Zone 5 reassessment of landslide risk following updated RAMMS debris flow modelling

2.4.2 Calibration observations

In general, the RAMMS modelling was able to be broadly matched to the total travel distance of the February 2023 landslides observed in the field. The following were observed during the calibration process:

- Simulated small debris flows travelled significantly further than in reality (see Figure D2 for an example of this). This is likely due to the resistance generated by large trees and dense vegetation. In addition, other factors may mean there is an insufficient supply of liquefied debris. Small debris flows would require a specific calibration to provide a credible model.
- The debris flow terminal lobe modelled as being wider in the northern part of Motutara Road (see Figure D3). This could be due to the influence of large trees or buildings, several of which were destroyed in the event.
- Relatively thin layers (less than 200 mm) of debris modelled as affecting areas that were not damaged by debris flows (see Figure D4).
- Stop criteria – the default values provided in RAMMS are adequate, as confirmed by our stop criteria analysis (see Figure D6).

D2.5 Sensitivity analysis

A sensitivity analysis tests the influence of individual model parameters to help understand the relative importance of the elements upon which the model is based. It provides focus for the critical input parameters. The process involves performing repeated RAMMS simulations with a change in one parameter, usually to an extreme high and/or low value. The parameters that were tested are discussed below.

Basal friction parameter Mu

This was tested in approximately 20 simulations using a range of Mu = 0.05 to 0.5. The RAMMS simulation was very sensitive to Mu, with runout varying by more than 50 m downslope (see Figure D10).

Viscous-turbulent frictional parameter Xi

This was tested in approximately 16 simulations using a range of Xi = 5 to 200 m/s^2. The results are nearly identical showing the simulation is not sensitive to Xi (see Figure D11). A comparison of the debris flow extent of Xi = 87.5 m/s^2 (the GHD-selected value) and 150 m/s^2 (RAMMS, 2022 mid-range value) also showed minimal difference in debris flow extent – mostly less than 1 m horizontally (see Figure D12). Broader, less channelised flows travel slightly further with Xi =150 m/s^2.

Erosion function

Although the erosion function was not considered appropriate for use at Muriwai, the sensitivity of its use was tested by comparing the simulated distribution of debris with the function turned on and off. This confirmed that the simulation is not sensitive to the erosion function (see Figure D13).

Multiple block release

Our simulation does not predict which landslide sources will become debris flows in a particular event, instead presenting the debris flow potential for all sources at one time. We have tested to see if there is an effect of multiple adjacent simulated landslides coalescing and travelling further than would be the case of an individual landslide. To do this, the debris flow runout for three landslide sources was simulated individually, then all three sources were simulated simultaneously (see Figure D14).

This showed that modelling coalescing of failures from numerous landslides increases the debris flow runout distance only slightly at Muriwai – typically less than 1 m horizontally, but up to 4 m in some areas.

D2.6 Inferred future landslide source areas

Potential landslide failure zones have been identified based on having similar geomorphology (ground shape) and geology to February 2023 landslide source areas. For example, the bowl-shaped head-scarp shape of recent landslides observed at the crest of the escarpment is similar to the shape of the escarpment where failures did not occur in 2023 (see Figure D9 in Appendix D-1) but have almost certainly occurred at some time in the past. The susceptibility of landslides across the study area has been inferred as variable, however, as a function of the local topographical landform. This is defined as 'geomorphological landslide zones' and outlined in further detail in Section B6.3.. We have assumed that future landslides on the escarpment have the potential to fail with similar damaging effects as the February 2023 landslides. Inferred future landslides were used as RAMMS debris flow source areas.

D3. Final model and analysis results

D3.1 Final simulation input parameters

The key parameters of Mu and Xi used for the prediction of future failure runout distances (the 'predicted' scenario) are those calibrated from the extent of February 2023 debris flow runouts. In addition, we tested the runout using conservative and non-conservative values (see Table D7).

The post-February 2023 DEM was used to model future potential debris flow. The release area applied to all landslide source areas (i.e., existing landslide areas and potential future landslide areas).

Table D7 Frictional parameters for the predicted debris flow runout. Conservative (worse case) and optimistic values are presented for comparison.

RAMMS input type	Input parameter Mu	Input parameter Xi (m/s^2)	Colour in Fig A201	Colour in A203-A206
Predicted	0.225	87.5	🟥	🟥
Non-conservative (optimistic)	0.3	75	🟩	Not shown
Conservative (worst case)	0.15	200	🟨	- - - - - - - -

Geomorphological Zone 5

The parameters used in Zone 5 are presented in Table D8.

Table D8 Frictional parameters for the predicted debris flow runout. Conservative (worse case) and optimistic values are presented for comparison.

RAMMS input type	Input parameter Mu	Input parameter Xi (m/s^2)	Colour in Fig A201	Colour in A203-A206
Predicted	0.4	500	🟥	🟥
Non-conservative (optimistic)	0.4	500	🟩	Not shown
Conservative (worst case)	0.4	100	🟨	- - - - - - - -

D3.2 RAMMS debris flow results

The outputs from the RAMMS debris flow analysis have been filtered and variously presented to illustrate a scientific and defensible modelling approach. Care should be taken to use the information in the intended context.

The presented A3 results figures associated with this report (listed in Table D2 and presented in Appendix A) in the escarpment area are as follows:

- **A201** – which shows the modelled debris extents for the non-conservative (optimistic) case, predicted and conservative (worst) case scenarios. It is filtered to show all depth above 0.01 m (1 cm). Importantly, it shows the 'F-angle' estimated runout zone used by AC to inform property the initial placard assignment. **This should be viewed only for general information and understanding RAMMS.**
- **A202-A205** – shows the modelled debris extents and maximum depth for the predicted scenario. It is filtered to show all depth above 0.01 m (1 cm). **This should be viewed only for general information and understanding RAMMS.**
- **A206-A209** – show the predicted modelled runout for debris flows that are greater than 0.5 m (50 cm) deep. Debris flows of or greater than this depth are considered to have the potential to severely damage or destroy a dwelling, if impacted (detailed in Section E4.6 of Risk Assessment Report in Appendix E). **These should be viewed to understand the potential modelled effects of debris flows on individual dwellings.**

The above results include the Zone 5-specific modelling.

D3.3 Data presentation in plans

We have made the following modifications to the raw RAMMS output to clarify the information in Figures A206-A209:

- Smoothing of lines – the output is a blocky line that has been manually smoothed (see Figure D15).
- Removing debris flow shading from the landslide source area – the RAMMS output shows red shaded debris in the source area. This has been removed so this area is not obscured. Occasionally it is left in where a dwelling is nearby to demonstrate the hazard (see Figure D16).
- In some areas there are small zones a few metres wide that have less than 0.5 m debris thickness modelled. For simplicity, these have not been shown as the hazard to dwellings is not changed by them (see Figure D17).
- Isolated zones of predicted debris flow – there are some instances of isolated zones, or islands, of modelled debris. These do not intuitively look correct, however, they can be explained as being due to the flow passing over uneven terrain and being below the 0.5 m filter when going over a crest (e.g. as for a waterfall) and accumulating in a low point (see Figure D18).

D3.4 Simulated escarpment debris flow results compared to property placard status

The following observations can be made about the extent of predicted escarpment RAMMS debris flow results (greater than 0.5 m thick, i.e. potentially causing fatalities) in relation to red placarded properties:

- The modelled debris flow reaches approximately two-thirds of red placarded properties.
- Most of these properties are close to the escarpment (i.e., the landslide source)
- Localised topographic variations have directed simulated debris flows towards some houses and away from others.

Yellow placarded properties are mostly outside of the predicted simulated debris flow of greater than 0.5 m.

D3.5 Quantification of overlap of actual compared with modelled debris flow runout area

To measure the agreement of our RAMMS calibration with debris flow runout extents, we support our qualitative, visual comparison of modelled results with a quantitative assessment using the methodology set out in Heiser et al. (2017)[5]. This quantifies the amount of overlap between landslide debris runout and that modelled in RAMMS. The parameters used and calculations are presented in Table D9. A visual representation of the assessment is presented in Figure D19.

Table D9 Summary of calculations for overlap of actual compared with RAMMS modelled debris flow runout area

Parameter	Formulae	Comments
Ω: Fitting parameter	$\Omega = \alpha - \beta - \gamma$	Possible range of 1 (perfect fit) to -1 (no overlap)
α: Overlap ratio	$\alpha = \frac{X}{T}$	Is the ratio of overlap runout area (X) to the total combined footprint of the simulated and observed runout area (T)
β: Underestimation ratio	$\beta = \frac{U}{T}$	Is the ratio of underestimation of debris in the model (underestimated modelled runout area (U) / the total combined footprint of the simulated and observed runout area (T))
γ: Overestimation ratio	$\gamma = \frac{O}{T}$	Is the ratio of overestimation of debris in the model (overestimated modelled runout area (O) / the total combined footprint of the simulated and observed runout area (T))

Graphs showing the relative amounts of the overlap parameters are presented in Figure D20 and Figure D21 in Appendix D-1. This analysis indicates the following:

- More than half of the RAMMS simulated debris flow area overlap with the observed runout area for each landslide sources considered in the calibration process (i.e. α is greater than 50%)
- There is minimal underestimation of the runout by the RAMMS simulation (i.e. β is less than 0.1)
- There is some overestimation of the runout by the RAMMS simulation (i.e. γ is between 0.2 and 0.5)

The resultant fitting parameter (Ω) values are all greater than zero, indicating a reasonable fit that is not overly dominated by underestimation or overestimation. We interpret this to mean that that the calibration has a reasonable balance of fit.

Table D10 Values calculated for fitting parameter Ω

Landslide Area ID	Ω
M-LS01	0.2
M-LS02	0.3
M-LS03- M-LS04	0.4
M-LS06-LS10, M-LS34	0.5
M-LS18- M-LS22	0.2
M-LS23	0.1

---

[5] Heiser M., Scheidl C. and Kaitna R. (2017). Evaluation concepts to compare observed and simulated deposition areas of mass movements. Comput Geosci, 21:335-343

D4. Conclusions

- A robust RAMMS debris flow analysis has been conducted using simulated landslide sources areas similar to the damaging February 2023 Cyclone Gabrielle, and from potential, future sources.
- Geomorphological Zone 5 landslides have been used to calibrate specific parameters for RAMMS analysis due to the relatively short debris flow runout distance when compared to other zones.
- A quantitative comparison of the actual landslide runout areas with that determined from RAMMS simulation indicates a reasonable fit.
- The predicted outcome of the simulation is that over 40 currently red-placarded dwellings could be subjected to impact by escarpment landslide debris that is greater than 0.5 m thick as shown on Figures A206 and A209. This has been assessed by GHD’s risk assessment in Appendix E as having the potential to cause fatalities, especially if large trees are mobilised by the landslide.
- Yellow placarded properties are largely beyond the extent of the escarpment landslide debris that is greater than 0.5 m thick.
- The RAMMS predicted runout extent of damaging debris (i.e. more than 0.5 m maximum thickness) is in broad agreement with the ‘F-angle’ empirical landslide hazard prediction work undertaken by AC to allocate the original emergency property placards.

D5. Limitations

This report has been prepared by GHD Limited (GHD) for Auckland Council and may only be used and relied on by Auckland Council for the purpose agreed between GHD and Auckland Council as set out in Section 1 of this report.

GHD otherwise disclaims responsibility to any person other than Auckland Council arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

The opinions, conclusions and any recommendations in this report are based on assumptions made by GHD described in this report (refer Section 1 of this report). GHD disclaims liability arising from any of the assumptions being incorrect.

An understanding of the geotechnical site conditions depends on the integration of many pieces of information, some regional, some site specific, some structure specific and some experienced based. Hence this report should not be altered, amended, abbreviated, or issued in part in any way without prior written approval by GHD. GHD does not accept liability in connection with the issuing of an unapproved or modified version of this report.

Verification of the geotechnical assumptions and/or model is an integral part of the design process - investigation, construction verification, and performance monitoring. If the revealed ground or groundwater conditions vary from those assumed or described in this report the matter should be referred back to GHD.

Appendices

Appendix D-1

Figures

The following is a presentation of RAMMS debris flow analyses outputs. All figures have North to the top of the page.

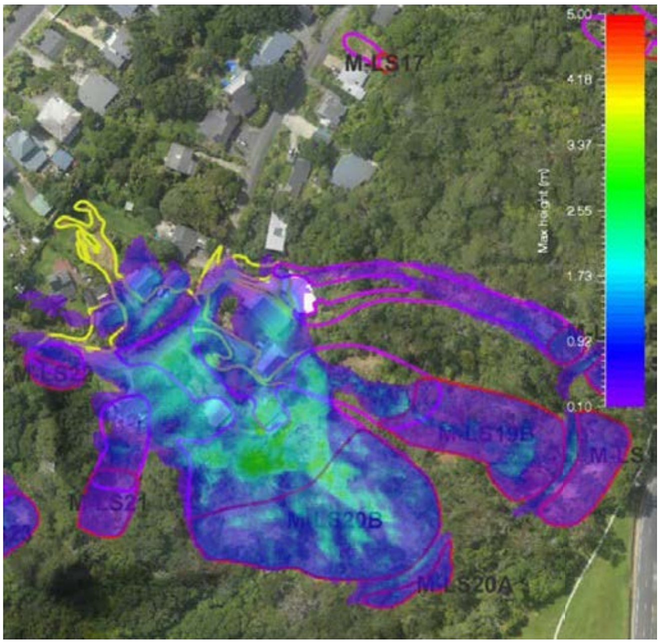


Figure D2 ***Best calibration of large slides southeast of Domain Crescent (M-LS18A, 18B, 19A, 19B, 20A, 20B, 21, 22 & 23). Mu = 0.225, Xi = 87.5, showing with 0.01-5 m filter. Note small landslide on the left that modelled as travelling further than observed.***

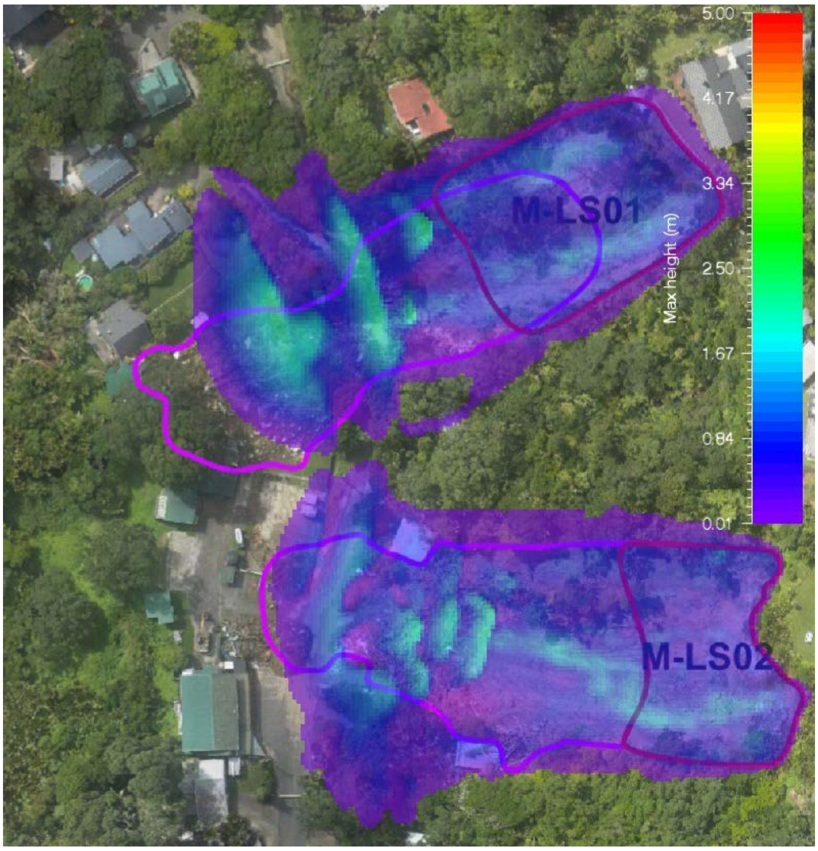


Figure D3 ***Best calibration of large slides at north end of Motutara Road (ID M-LS01 and M-LS02). Mu = 0.225, Xi = 87.5, showing with 0.01-5 m filter. Note modelled debris flow lobe is wider than observed.***

Figure D4 **Best calibration of large slides at Motutara Road (M-LS03, M-LS04A and M-LS04B). Mu = 0.225, Xi = 87.5, showing with 0.01-5 m filter**

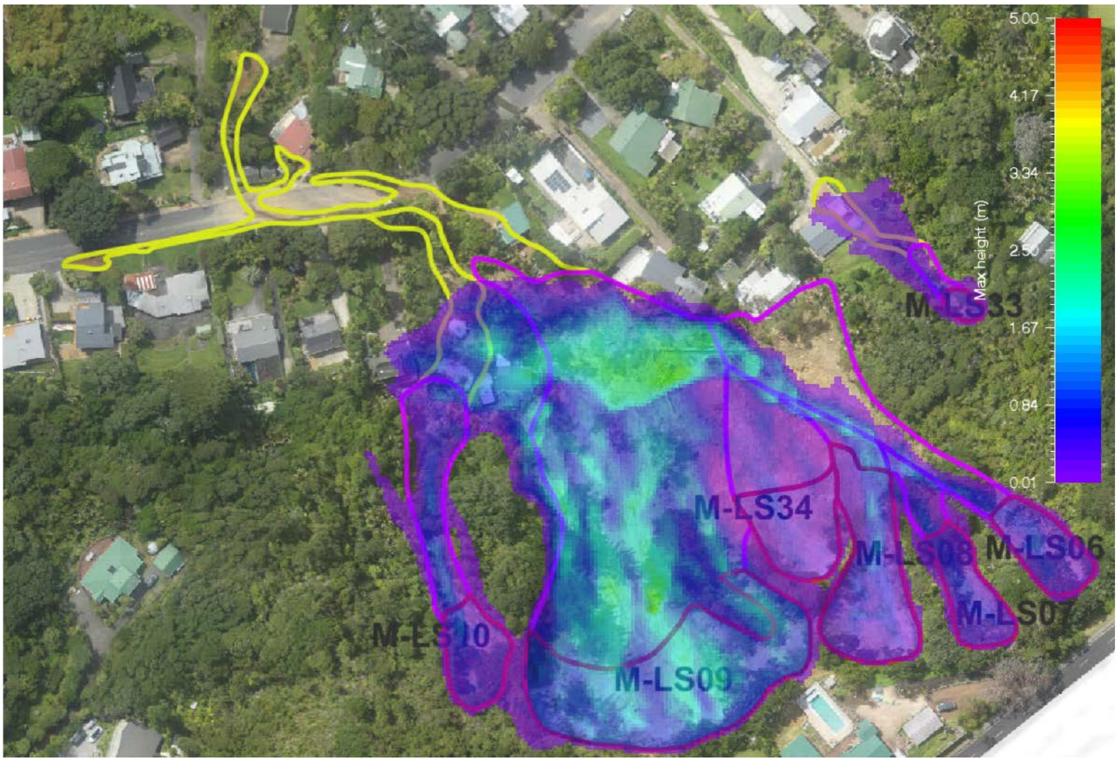


Figure D5 **Best calibration of large slide at Motutara Road (M-LS06, 07, 08, 09, 10, 33 & 34). Mu = 0.225, Xi = 87.5, showing with 0.01-5 m filter**

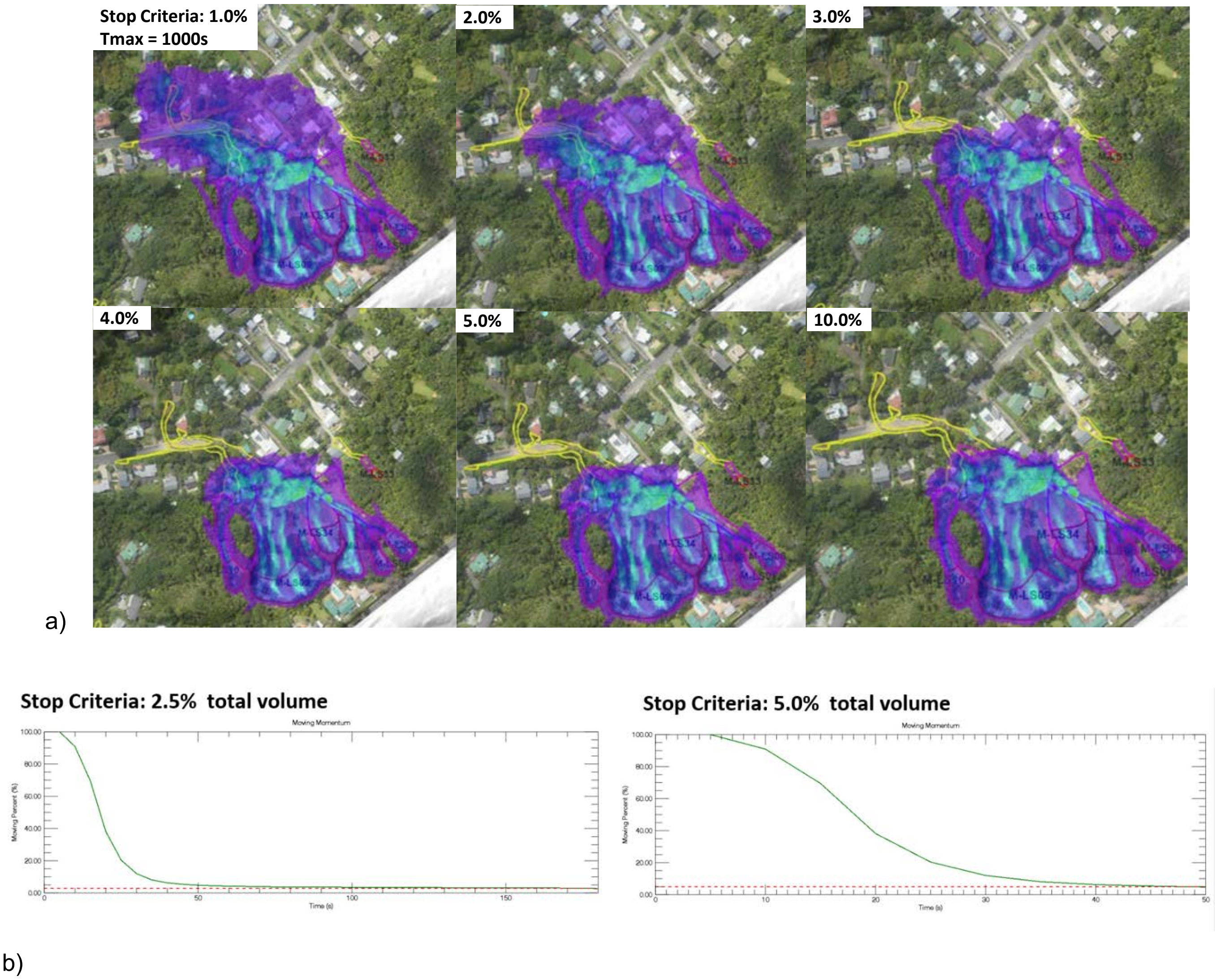


Figure D6 *The selection of the RAMMS momentum-based 'Percentage total momentum' stop criteria (for Xi = 150 m/s^2 and Mu = 0.2).*
a) The percentage value of less than 5% shows a wide, creeping debris flow at the end of the simulation (showing 0-5 m maximum debris thickness). For scenarios above 5% the simulated debris extents is similar.
b) The relationship between Moving Percent with time. This shows that a lower percentage total volume Stop Criteria (left), indicated by the red line, leads to longer runout times than when a higher percentage total volume is selected (right). If the lower percentage is used, the result is a debris flow extent that slowly expands towards the end of the simulation.

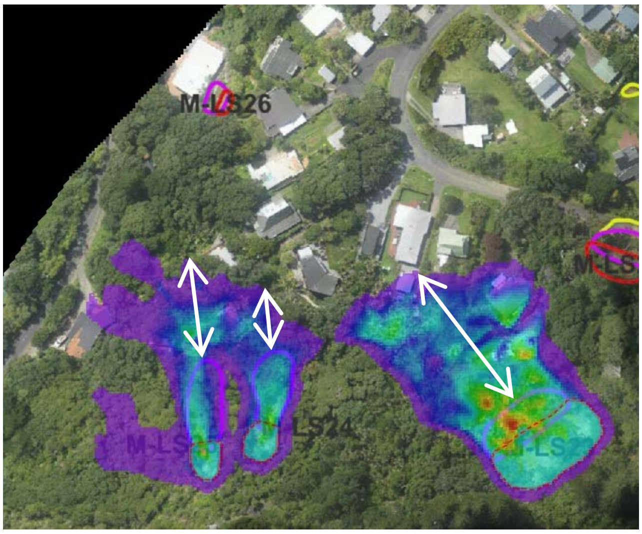


Figure D7 Zone 5 RAMMS simulation showing how the use of (Revision 0) analysis parameters are overly conservative. White arrows show the debris travelling beyond the mapped landslide extents.

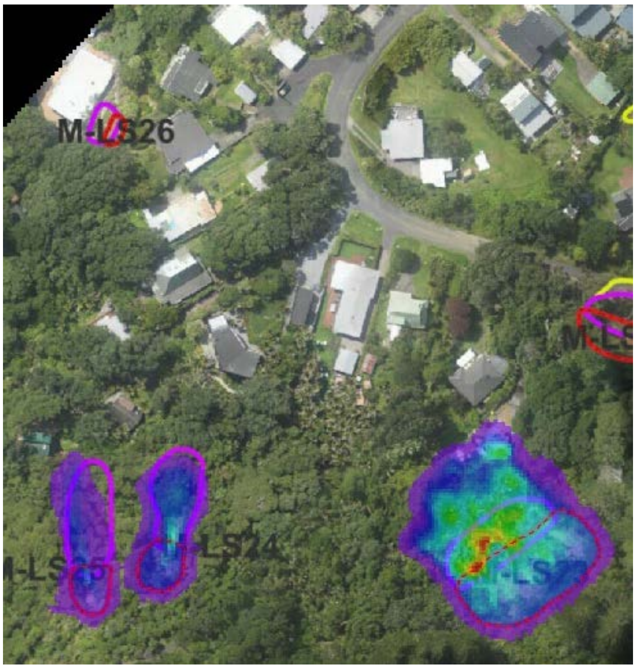


Figure D8 Zone 5 RAMMS calibration using parameters that gives the best match to observed landslide runout

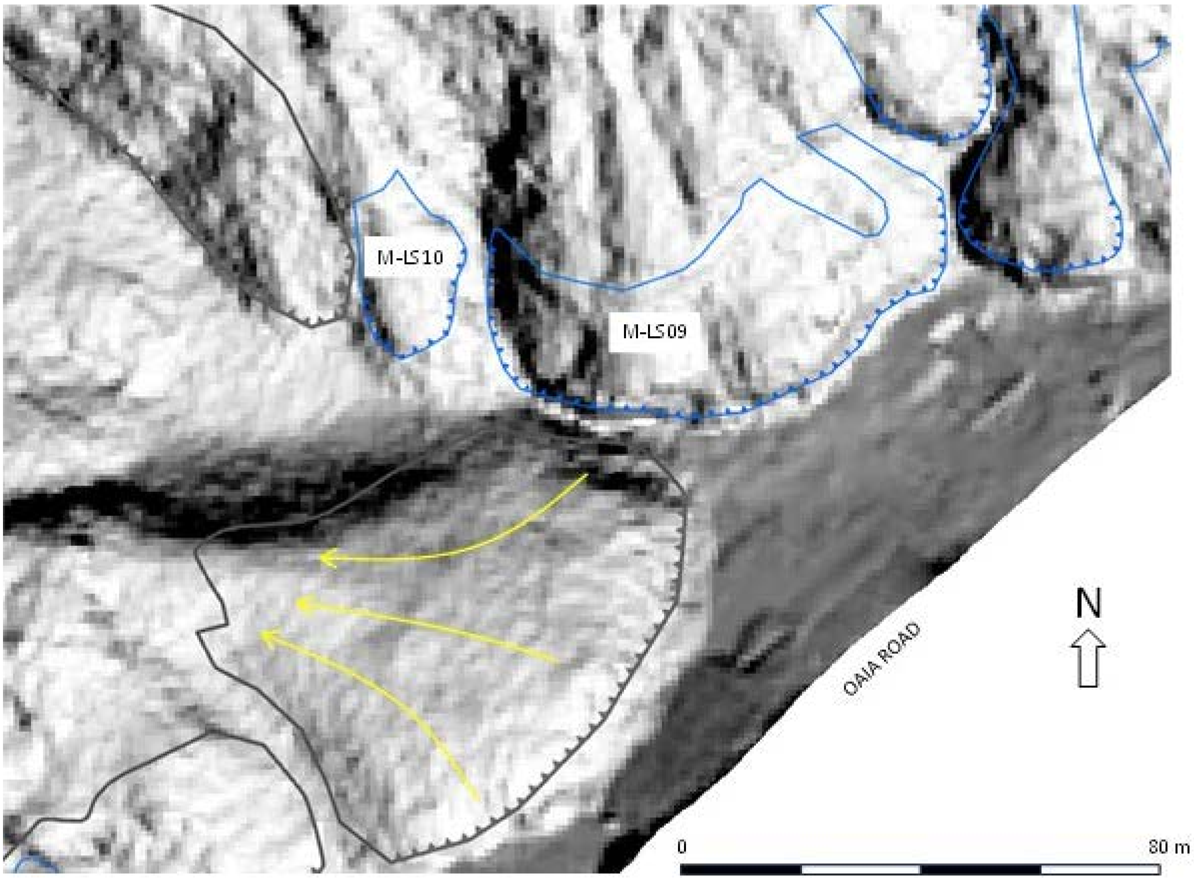


Figure D9 *Potential landslide failure zones have been defined by GHD based on having similar geomorphology (ground shape) and geology to February 2023 landslide source areas. The above example shows a potential landslide source zone (grey outline) that has similar bowl-shaped characteristics to recently failed blue areas. Background surface model has a 'hill shade' applied to highlight the geomorphology. Location is below the escarpment and west of Oaia Road (see Figure A115 in Appendix A).*

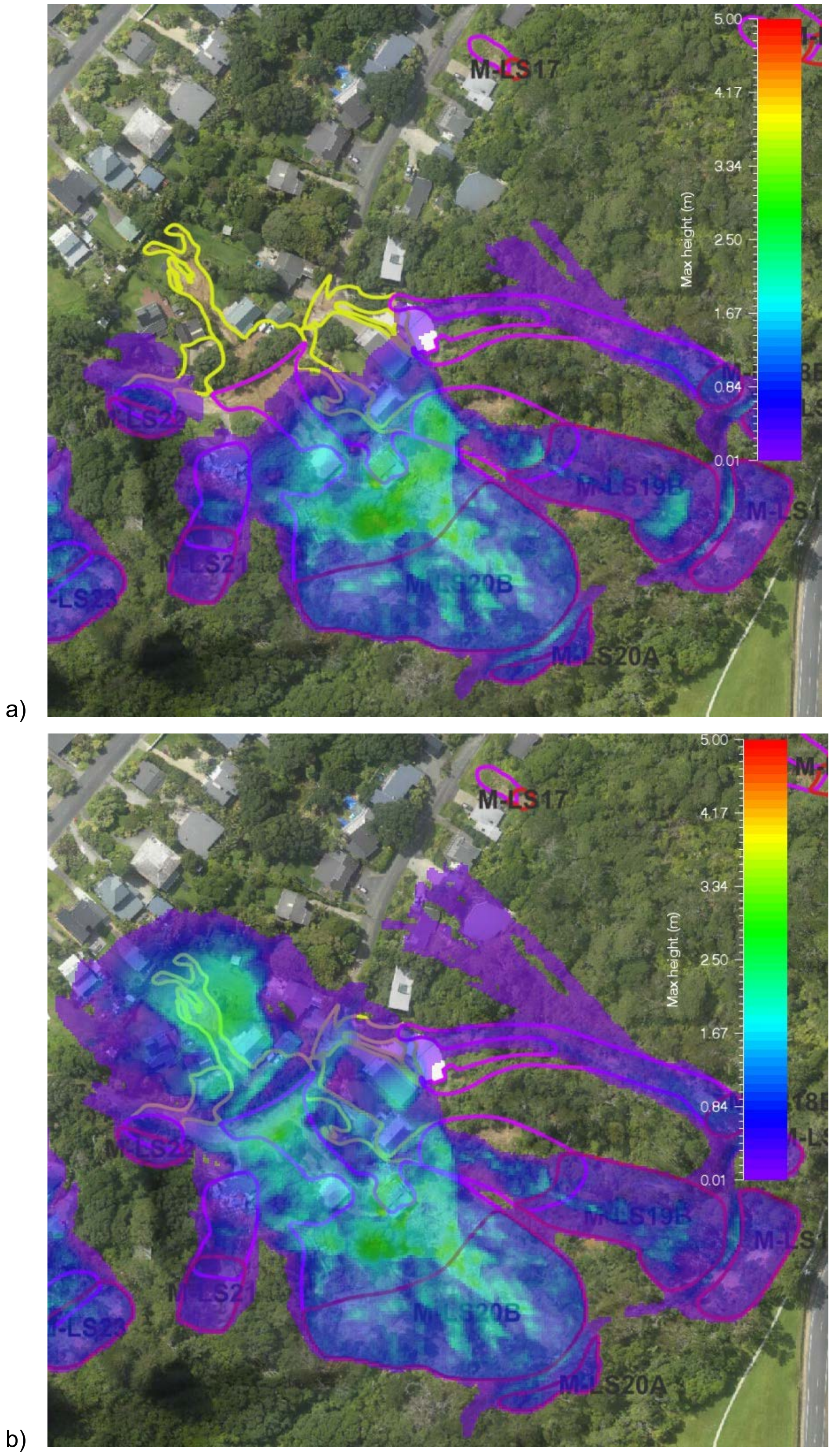


Figure D10 *Comparison of RAMMS input parameter Mu (basal friction), with a) Mu = 0.3 and b) Mu = 0.15. All other parameters are unchanged. Note that simulated debris travelled much further with the lower Mu value.*

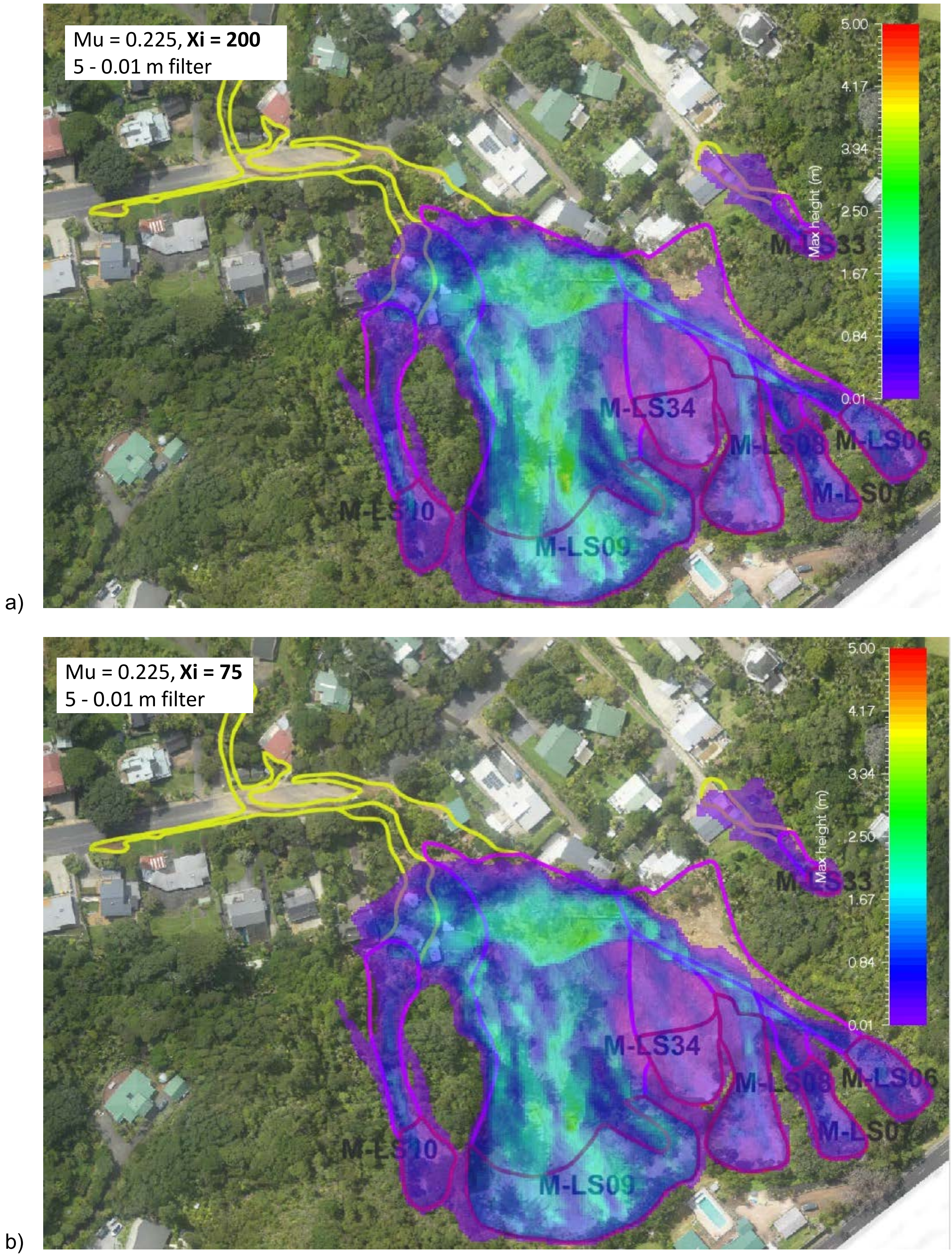


Figure D11 ***Comparison of RAMMS input parameter Xi (viscous-turbulent friction), with a) Xi = 200 and b) Xi=75. All other parameters are unchanged. Note that the results are nearly identical, and the simulation is not sensitive to Xi.***

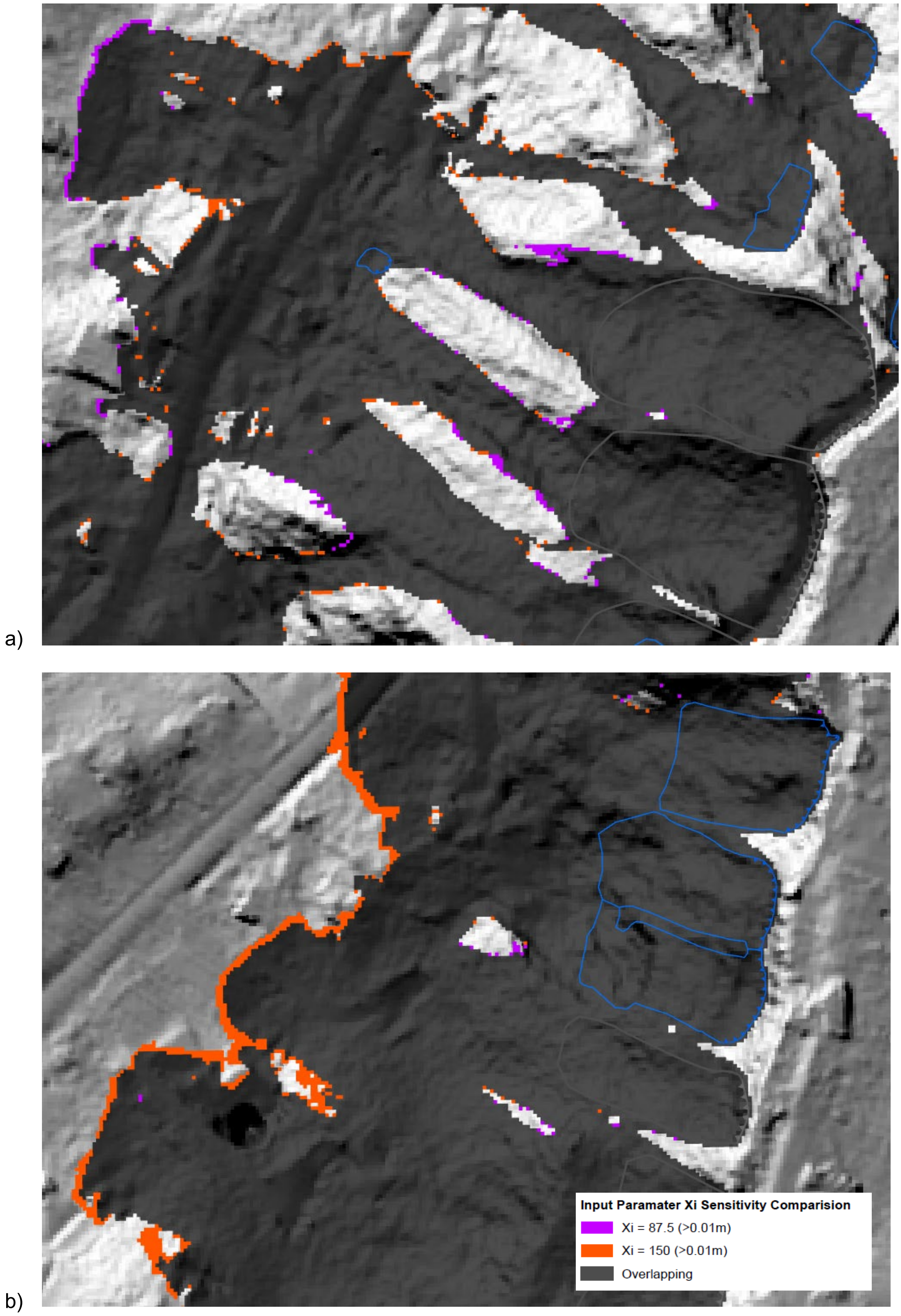


Figure D12 ***Comparison of RAMMS input parameter Xi (viscous-turbulent friction), with the simulated debris flow extent of Xi = 87.5 m/s^2 (the GHD-selected value) and 150 m/s^2 (RAMMS, 2022 mid-range value) overlain to highlight the difference. Each pixel is 1 m^2. a) is uphill of Domain Crescent and b) is uphill of Motutara Road. The difference in debris flow extent is mostly less than 1 m (horizontal). Broader, less channelised flows travel slightly further with Xi =150 m/s^2.***

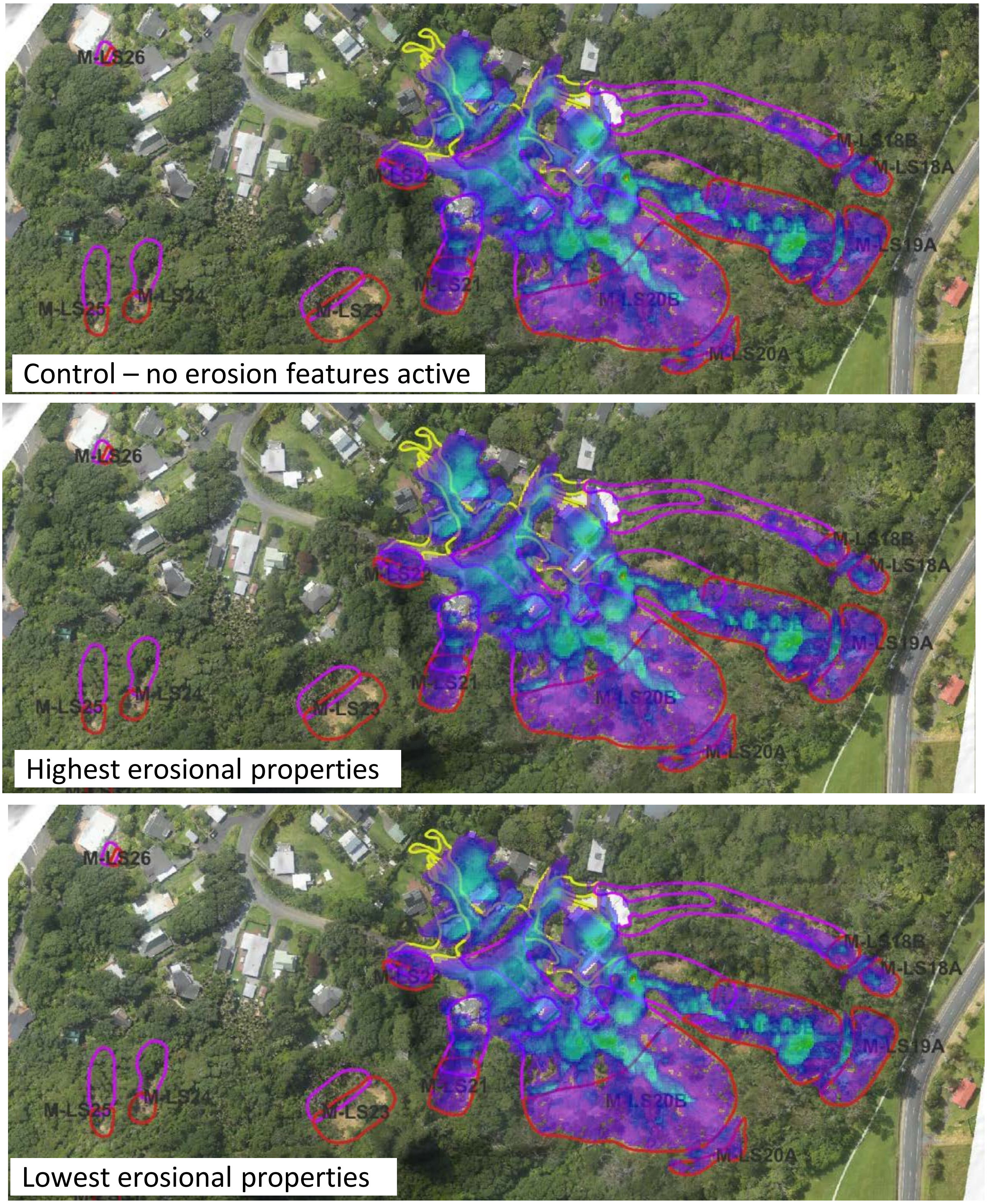


Figure D13 ***An example of the comparison of the erosional parameters input parameter showing negligible difference between the high and low erosion scenarios, compared with when no erosion features are used.***

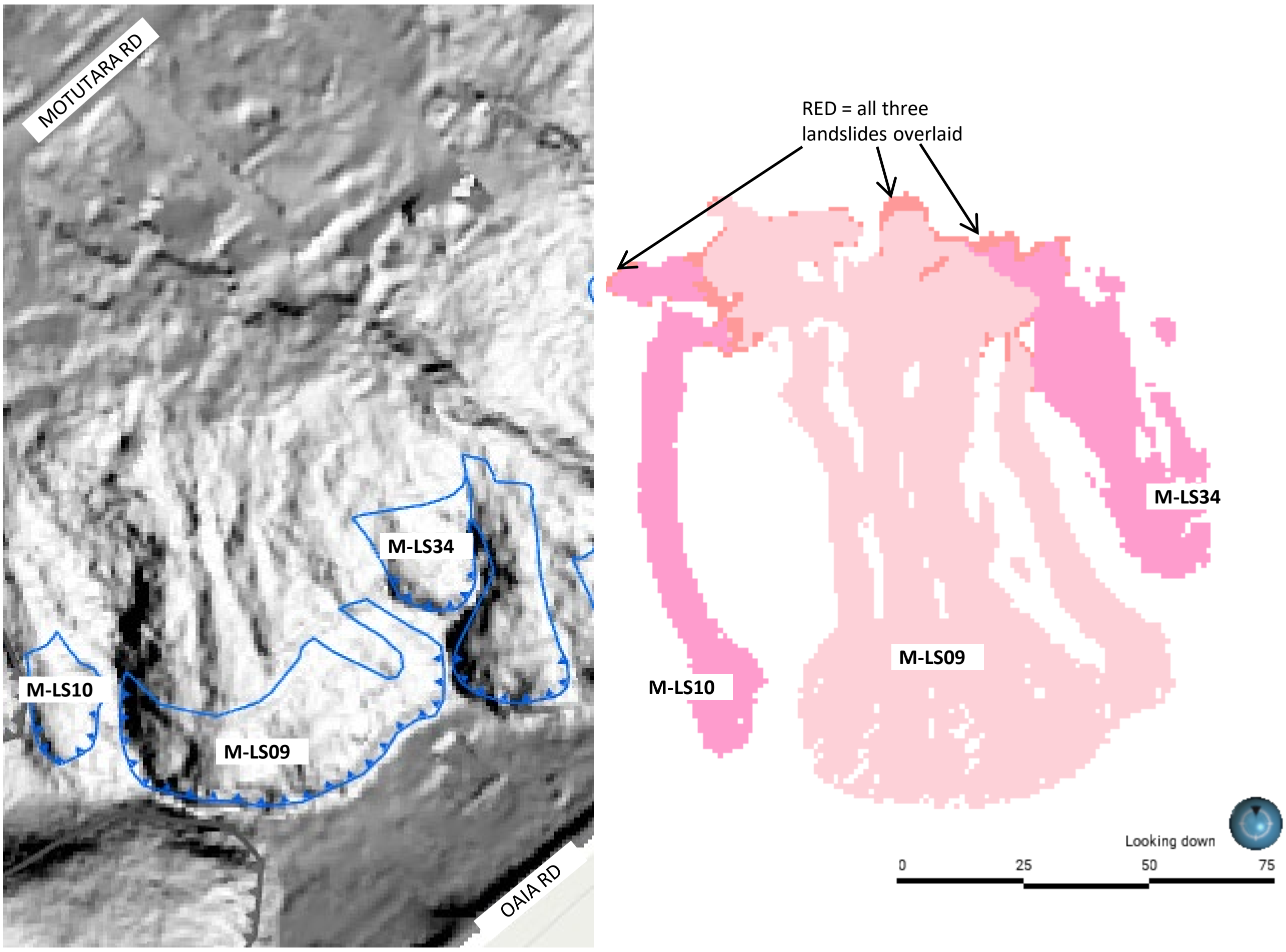


Figure D14 ***Multiple block release versus individual release comparison. The debris flow runout for three landslide sources was simulated individually (light pink and dark pink on the right image), then all three sources were simulated simultaneously (red shading). Each pixel is 1 m^2. This shows that modelling failures from numerous landslides increases the debris flow runout distance only slightly – typically less than 1 m horizontally, but up to 4 m in some areas.***

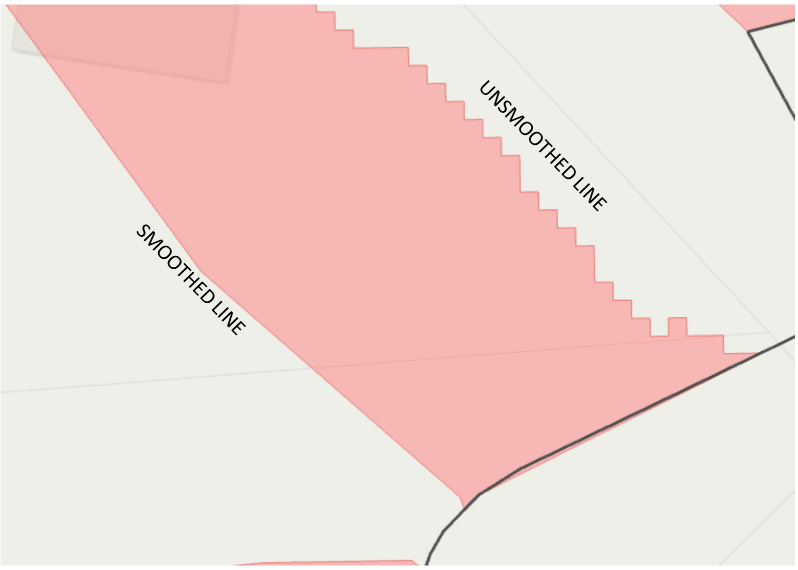


Figure D15 ***Example of where the predicted red debris flow has been manually smoothed (left side) compared with the right side of the red shading, which is the RAMMS output.***

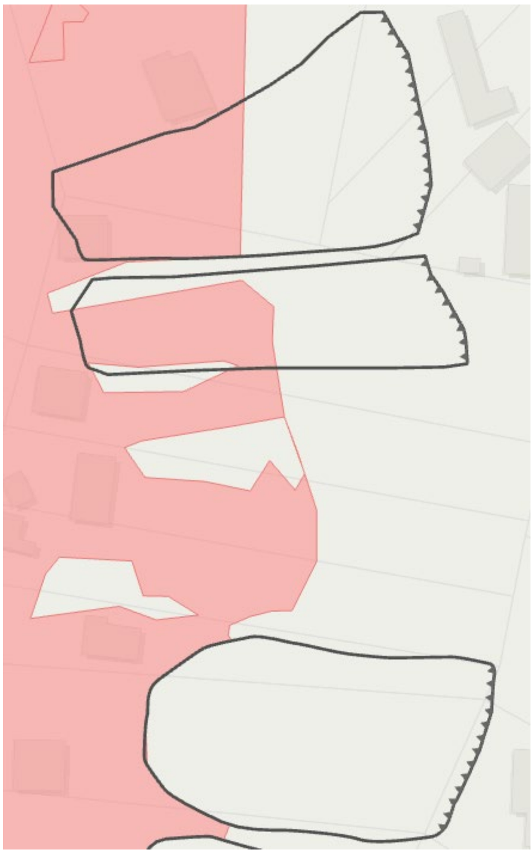


Figure D16 *An example of where the red debris flow shading has been removed from the landslide source (bottom of picture), but has been left in when near a dwelling (top of picture)*

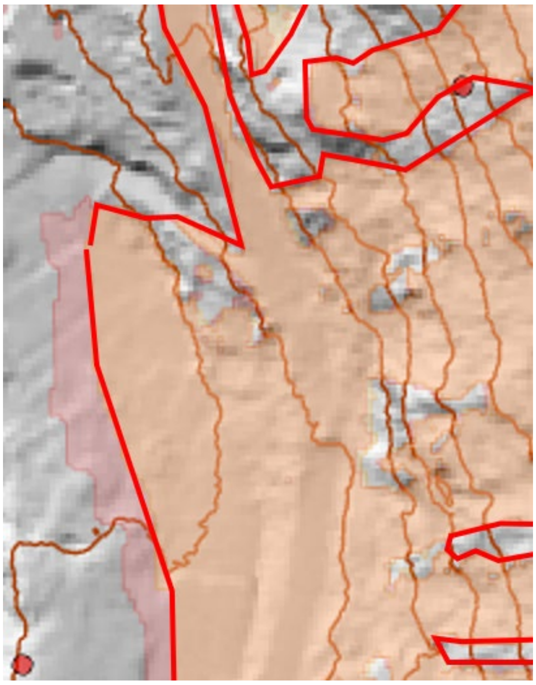


Figure D17 *An example of simplification of the predicted debris extent (shown in orange in this work-in-progress example). The thick red line is the edge of the predicted zone in the figures, with the small patches that are less than 0.5 m (shown as grey) not included.*

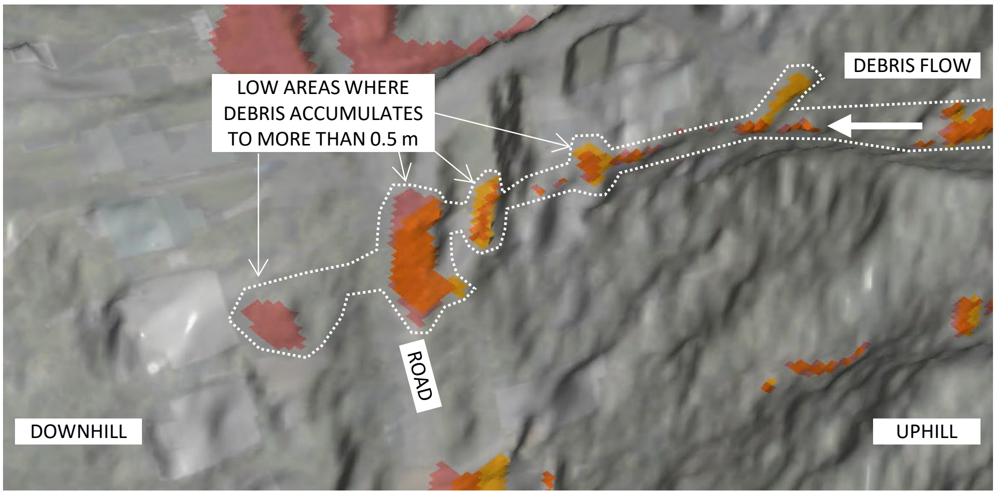


Figure D18 *An oblique view of predicted debris flow showing how isolated islands can occur due to the highs and lows of the surface topography.*

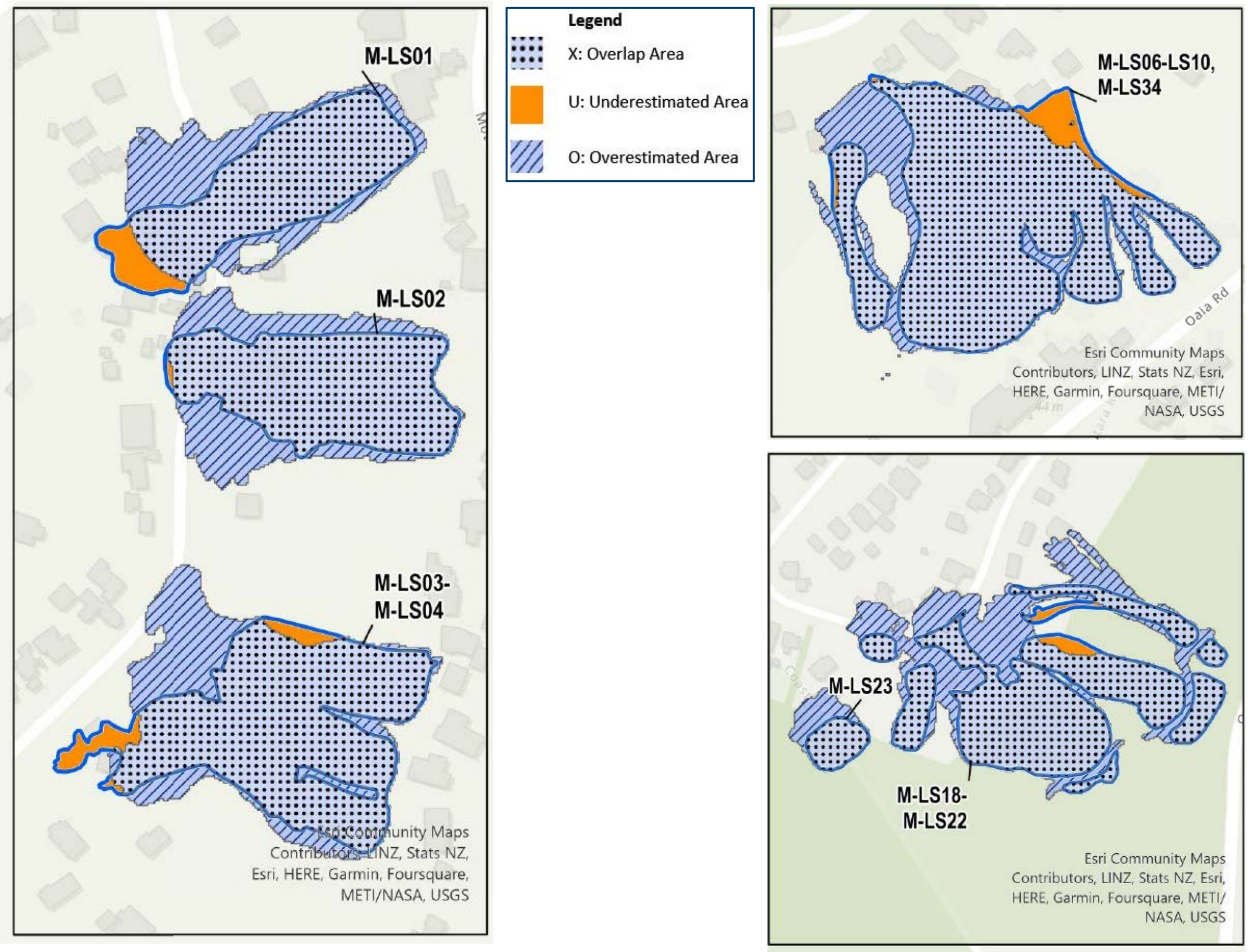


Figure D19 *Illustration of the area parameters used for calibration quantification*

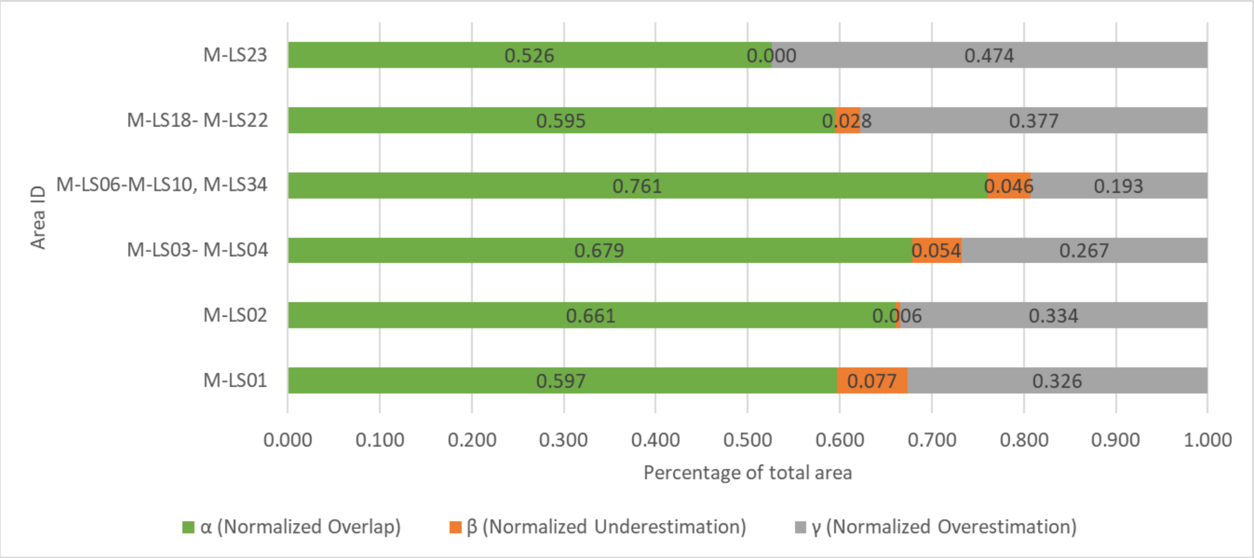


Figure D20 ***Parameters α, β and γ for each landslide***

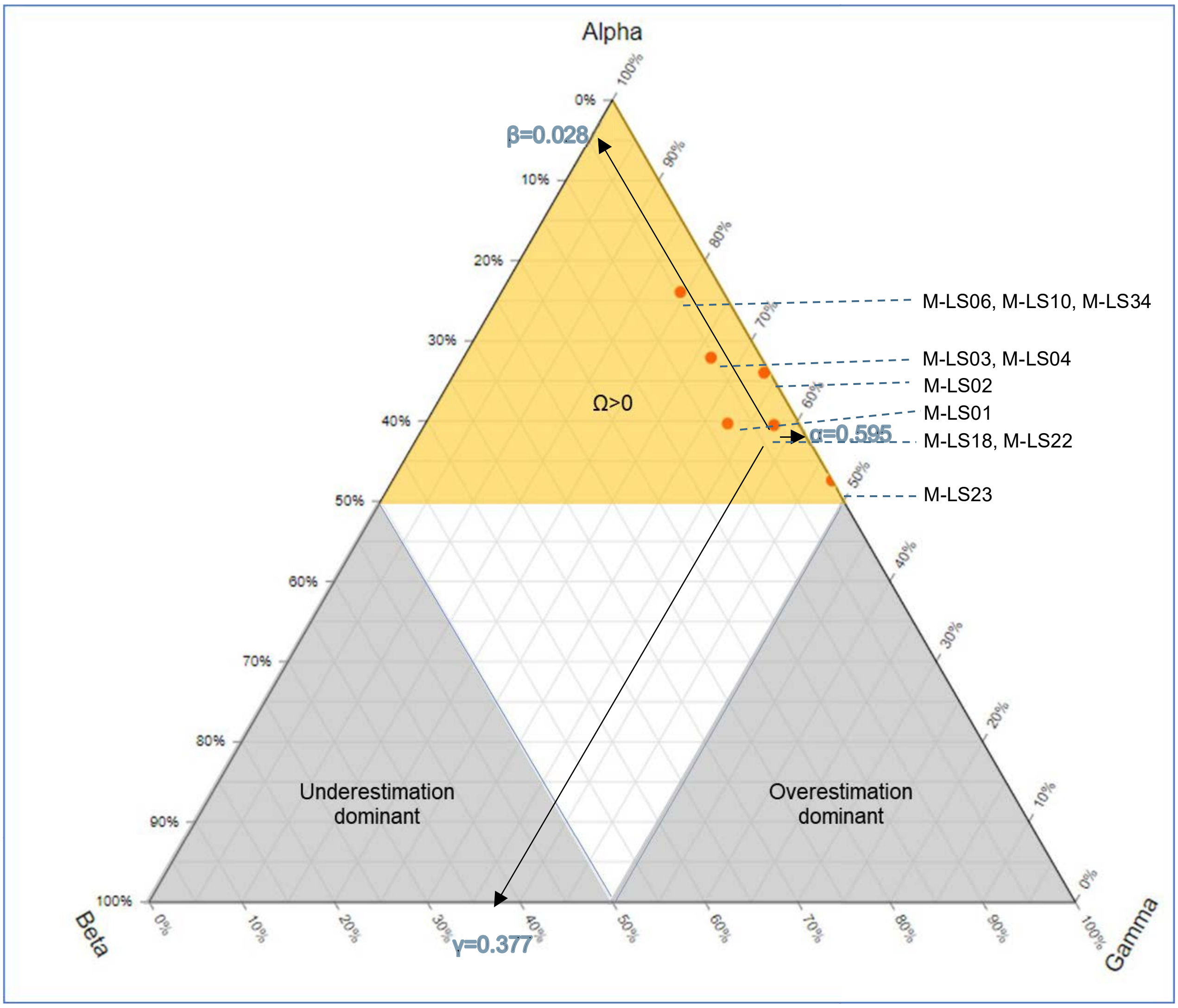


Figure D21 ***Ternary plot showing the debris flow simulated with RAMMS for the observed landslides used for calibration. Note that the latest calibration data is used for the landslides in Zone 5.***

Appendix E

Landslide Risk Assessment

Waitakere Coastal Communities

Appendix E – Muriwai Landslide Risk Assessment Report

Auckland Council

15 May 2024

→ **The Power of Commitment**

Project name	Waitakere Coastal Communities Landslide Risk Assessment
Document title	Waitakere Coastal Communities | Appendix E – Muriwai Landslide Risk Assessment Report
Project number	12612462
File name	12612462_Appendix E Risk_FINALRev2.docx

Status Code	**Revision**	**Author**	**Reviewer**		**Approved for issue**		
			Name	**Signature**	**Name**	**Signature**	**Date**
S4	0	A. Hunter	Don Macfarlane	D Macfarlane	Roy Pearson	Roy Pearson	03/11/2023
S4	1	A. Hunter M. Howard	Don Macfarlane	D Macfarlane	Roy Pearson	Roy Pearson	30/04/2024
S4	2	A. Hunter M. Howard	Don Macfarlane	D Macfarlane	Roy Pearson	Roy Pearson	15/05/2024

GHD Limited
Contact: Matt Howard, Technical Director - Engineering Geology | GHD
27 Napier Street, GHD Centre Level 3
Freemans Bay, Auckland 1010, New Zealand
T +64 9 370 8000 | **F** +64 9 370 8001 | **E** aklmail@ghd.com | **ghd.com**

The Power of Commitment

Contents

Table index

Figure index

Appendices

E1. Introduction

E1.1 Purpose of this report

GHD has been engaged by Auckland Council (AC) to carry out landslide risk assessments as well as to provide landslide risk management advice and geotechnical investigations in the Waitakere area, specifically for the residential areas of Muriwai, Piha and Karekare.

The purpose of this assessment is to present the results of a Quantitative Landslide Risk Assessment (QRA) carried out to estimate the risk of Loss of Life posed by large-scale[1] landslides to individuals in dwellings at Muriwai. We understand the outcome of the QRA will be used to inform future planning decisions, dwelling hazard designations and the revision of current building placards attached following Cyclone Gabrielle.

This report is an appendix to the overall GHD landslide risk report and should be read in conjunction with it, as well as associated appendices. The overall report contains additional background information and the results of other assessments carried out by GHD that are not included in this report. In particular, the GHD Muriwai Engineering Geological Report (hereafter referred to as the Appendix B report) provides a detailed description of the site as well as discussion of site geology and geomorphology, historical landsliding, landslide mapping, landslide classification and slope processes.

E1.2 Background

Two significant rainfall events affected the Waitakere area in late January and early February, resulting from the impacts of ex-tropical cyclones Hale and Gabrielle, respectively.

The Cyclone Gabrielle weather event of 14 February 2023 resulted in widespread catastrophic flooding and slope instability in the settlement of Muriwai where several debris avalanches (which included rocks and entrained trees) occurred, some of which turned into saturated debris flows. These flows resulted in damage to buildings and infrastructure. Two fatalities occurred due to impact of landslides on private dwellings. In 1965 a storm also triggered landslides that destroyed dwellings and claimed two lives at Muriwai.

Following the event, rapid building assessment of residential properties was undertaken by Auckland Council in Muriwai, with some houses having access by owners restricted (a yellow placard – e.g. access in daylight hours only) and some for which no access was permitted (a red placard). AC adjusted the location of placards following an area-wide Fahrböschung angle ('F-angle') assessment[2]. The current classifications are indicated by red or yellow dots in the attached figures.

The 'F-angle' assessment roughly estimates the maximum likely distance that a landslide will travel, taking into account the relative location of potentially at-risk properties to the source of risk, i.e. the hazardous slopes of the Muriwai Escarpment. Although the assessment criteria are relatively simplistic and conservative, the 'F-angle' provides a technical basis for classifying (placarding) properties quickly, which was appropriate for the rapid building assessments undertaken where decisions to evacuate people were required urgently.

E1.3 Scope

AC requested that this study be limited to the assessment of risks posed by 'large scale' landslide hazards originating from the main escarpment located to the south-east of Muriwai because the initial placard assessment was largely aimed at mitigating risks associated with these landslide hazards. Consequently, this report does not consider smaller, more localised landslide hazards that could originate (or may have already initiated) from other areas in Muriwai, such as within the footprint of individual dwellings, except for three specific properties attached to this report (Appendix E-2, E-3, E-4). Further clarification of this is given in Section 1.3 (footnote 3).

---

[1] In this report 'large scale' landslide hazards refer to landslides originating from the main escarpment that typically have a volume of more than about 50 m^3 with the potential to cause total or partial collapse of a dwelling.

[2] Documented in an internal AC memo dated 9/03/2023, document ID: AKLCGEO-1790012875-1831

Smaller landslide hazards may include existing geohazards that have resulted from recent failures with the potential to pose risk to life in the immediate short-term (i.e. within the next few years) such as regression of translational failures that occur downslope of dwelling, failure of over-steepened fill and cut slopes, rockfall hazards associated with exposed rock faces/headscarps and/or loose debris remaining upslope of dwellings.

In addition, other possible geotechnical slope instability hazards relating to modified slopes (i.e. human made) may also exist and have potential to pose a risk to life - such as failures of fills, cuttings and damaged retaining walls. This represents hazards that may have a range of likelihood from *almost certain* to *possible*[3].

The QRA has been carried out in general accordance with the Australian Geomechanics Society Practice Note Guidelines for Landslide Risk Management, commonly known as AGS (2007c). A “risk to property” assessment was not part of our scope of work, which is specifically targeted on risk to life.

Dwellings that have been assessed to be in the path of landslide runout are considered as the elements at risk for this assessment. The risks posed to individuals in the ‘open’, such as people outside houses or situated on other public property such as roads, are not considered in this report.

Excluded from this report is consideration of the risk relating to dwellings located along the crest of the main escarpment (i.e. the west side of Oaia Road) that could be undermined by the regression of the escarpment edge during future landslide events. Commentary on escarpment edge regression is to be included in a separate, future study.

This report has appended to it landslide risk assessment reports for three individual properties at 85 and 87 Domain Crescent and 207 Motutara Road, Muriwai (see Appendix E-2, E-3 and E-4, respectively).

This assessment considers geotechnical matters only. There may be other non-geotechnical considerations that affect the final property risk categorisation or placard designation of which GHD are not aware, such as flood risk or structural damage to property.

Although considered unlikely, GHD reserves the right to amend the opinions, conclusions and recommendations provided within this report, should additional geotechnical information become available.

This report has been prepared by GHD for Auckland Council and may only be used and relied on by Auckland Council for the purpose agreed between GHD and Auckland Council as set out in section 1.1 of this report.

GHD otherwise disclaims responsibility to any person other than Auckland Council arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

The opinions, conclusions and any recommendations in this report are based on assumptions made by GHD described in this report. GHD disclaims liability arising from any of the assumptions being incorrect.

E1.4 Report structure

This report accompanies numerous other assessments associated with the Muriwai landslides. A list of companion reports is presented in Table E1. A3 plans referred to in this report are listed in Table E2 and additional images and data are presented in Appendices B-1, B-2 and B-3.

---

[3] The terminology used when referencing probabilities has been adopted from the Qualitative Measures of Likelihood table for assessing risk to property in AGS (2007c). For this assessment, these terms and associated probabilities are Certain = 0.99, Almost Certain = 0.1, Likely = 0.01, Possible = 0.001, Unlikely = 0.0001, Very Unlikely = >0.00001

Table E1 Summary of accompanying Muriwai reports

Report Section	Description
Overall Report	Waitakere Coastal Communities Landslide Risk Assessment (Muriwai)
Appendix A	Figures
Appendix B	Engineering Geological Report
Appendix C	Slope Stability Assessment
Appendix D	RAMMS Debris Flow Analysis
Appendix E	*Landslide Risk Assessment (this report)*
Appendix F	Geotechnical Investigations Report

Table E2 List of maps and images in Appendix A that are associated with this report

Figure No.	Description
GENERAL SITE LAYOUT	
A101	OVERVIEW
ENGINEERING GEOLOGICAL PLANS	
A111	LEGEND
A112	OVERVIEW
A113 -A116	CLOSE-UP PLANS
CROSS SECTIONS	
A120	CROSS SECTION A-A’
A121	CROSS SECTION B-B’
A122	CROSS SECTION C-C’
A123	CROSS SECTION D-D’
A124	CROSS SECTION E-E’
GEOMORPHOLOGICAL LANDSLIDE ZONES	
A125	SLOPE RELIEF AND PROFILE COMPARISON PLAN

E2. Landslide Risk Estimation

E2.1 Background

The 1998 Thredbo landslide (New South Wales, Australia), in which 18 persons were killed, highlighted the challenges faced from building upon steep slopes and led to the development of the Australian Geomechanics Society Landslide Risk Management (LRM) guidelines, published in 2007 and now commonly referred to as AGS (2007). This suite of guidelines is recognised nationally (Australia) and internationally as world-leading practice. The reader of this report is encouraged to consult the freely available LRM resources which can be accessed at: https://landsliderisk.org/.

Distilled down to its simplest form, AGS 2007c requires any landslide risk assessment to answer five questions as follows:

- What might happen? (Hazard Identification)
- How likely is it? (Likelihood or Frequency Analysis)
- What damage or injury might occur? (Consequence Analysis)
- How important is it? (Risk Estimation and Risk Evaluation)
- What can be done about it? (Risk Management).

The “Practice Note Guidelines for Landslide Risk Management” (AGS 2007c) provide technical guidance in relation to the processes and tasks to be undertaken by geotechnical practitioners who prepare LRM reports, including appropriate methods and techniques. The Practice Note is a statement of what constitutes good practice by a competent practitioner for LRM, including defensible and up to date methodologies, and provides guidance on the quality of assessment and reporting, including the outcomes to be achieved and how they are to be achieved.

The framework for landslide risk management is presented in Figure E1 and represents a framework widely used internationally.

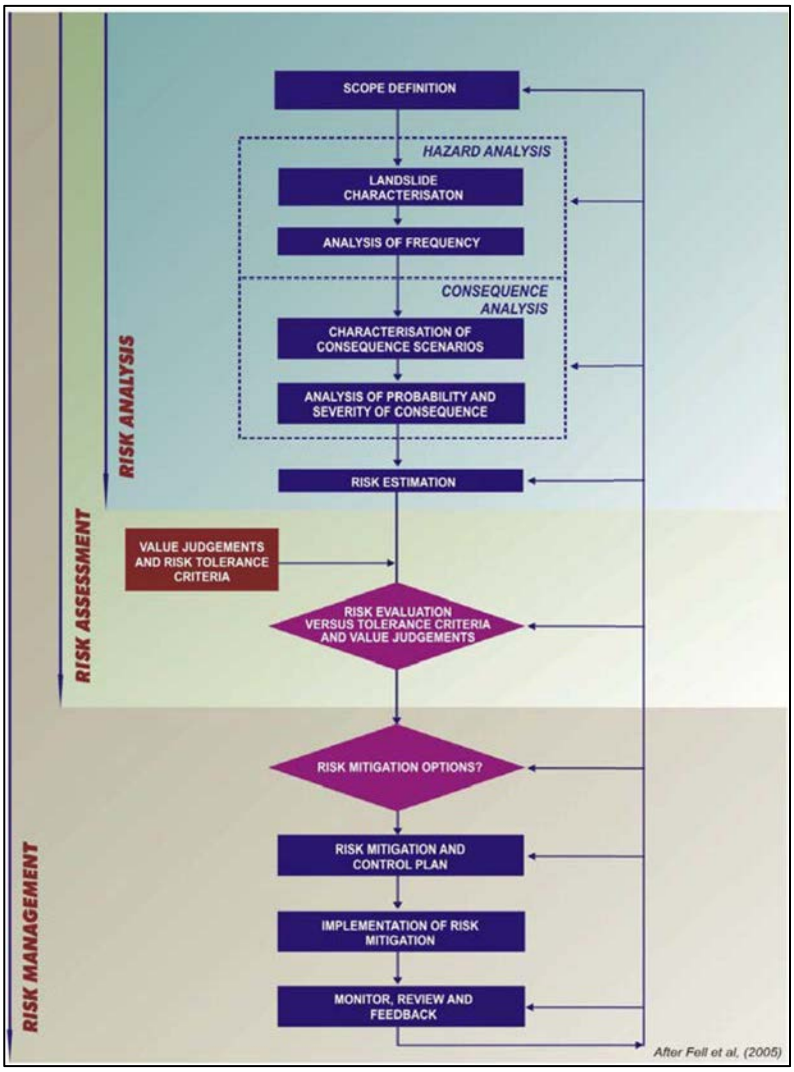


Figure E1 *Framework for landslide risk management.*

E2.2 Risk assessment methodology

AGS (2007c) requires risks to loss of life to be estimated quantitatively for the person-most-at-risk. The person-most-at-risk will often but not always be the person with the greatest spatial temporal probability (i.e. the person most exposed to the risk). The Individual Risk-to-Life is defined as the risk of fatality or injury to any identifiable (named) individual who lives within the zone impacted by the landslide; or who follows a particular pattern of life that might subject him or her to the consequences of the landslide. The risk of 'loss-of-life' to an individual is calculated from:

$$\mathbf{R}_{(LoL)} = \mathbf{P}_{(H)} \text{ x } \mathbf{P}_{(S:H)} \text{ x } \mathbf{P}_{(T:S)} \text{ x } \mathbf{V}_{(D:T)}$$

Where:

$\mathbf{R}_{(LoL)}$	is the risk (annual probability of loss of life (death) of an individual).
$\mathbf{P}_{(H)}$	is the annual probability of the landslide.
$\mathbf{P}_{(S:H)}$	is the probability of spatial impact of the landslide impacting a building (location) taking into account the travel distance and travel direction given the event.
$\mathbf{P}_{(T:S)}$	is the temporal spatial probability (e.g. of the building or location being occupied by the individual) given the spatial impact and allowing for the possibility of evacuation given there is warning of the landslide occurrence.
$\mathbf{V}_{(D:T)}$	is the vulnerability of the individual (probability of loss of life of the individual given the impact).

The main objectives of risk evaluation are usually to compare the assessed risk to risk levels that are acceptable or tolerable to the community, and therefore to decide whether to accept, tolerate or treat the risks, and to set priorities for remediation. The Tolerable Risk Criteria are usually imposed by the regulator, unless agreed otherwise with the owner/client. AGS (2007d) provides discussion and gives the AGS recommendations in relation to tolerable risk for loss of life. These are discussed in Section E2.3.

E2.3 Risk Evaluation

The main objectives of risk evaluation are usually to compare the assessed risk to risk levels that are acceptable or tolerable to the community, and therefore to decide whether to accept, tolerate or treat the risks and to set priorities for remediation. The Tolerable Risk Criteria are usually imposed by the regulator, unless agreed otherwise with the owner/client. AGS (2007d) provides discussion and gives the AGS recommendations in relation to tolerable risk for loss of life. These are summarized in the table below.

Table E3 AGS Suggested Tolerable loss of life individual risk

Situation	Suggested Tolerable Loss of Life Risk for the person most at risk
Existing Slope / Existing Development	10^{-4} per annum (1E-4 pa), or 1 in 10,000 pa
New Constructed Slope / New Development / Existing Landslide	10^{-5} per annum (1E-5 pa), or 1 in 100,000 pa

It is important to distinguish between “acceptable risks” and “tolerable risks”. AGS (2007c) states that:

Tolerable risks are risks within a range that society can live with so as to secure certain benefits. It is a range of risk regarded as non-negligible and needing to be kept under review and reduced further if practicable.

Acceptable risks are risks which everyone affected is prepared to accept. Acceptable risks are usually considered to be one order of magnitude lower than the Tolerable risks.

Appended to this report are GHD landslide risk assessment reports for three individual properties at 85 and 87 Domain Crescent and 207 Motutara Road, that were carried out at the request of AC (see Appendix E-2, E-3, and E-4, respectively). These differ from this area-wide risk study as they pertain to the hazard from localised slope instability within the property boundary. The methodology for these is explained in full in the report for each site and further details are not discussed in this report (the summary of risk for these sites is reproduced in Section E3.2 of this report).

E2.4 Landslide Risk Assessment Uncertainty

The process of risk assessment involves estimation of likelihood, consequence and risks based on available information for the study site. By its very nature much of the data, including historical and current inventories, may be incomplete while understanding of the triggering events has a degree of uncertainty attached to it. Judgement is required to estimate the nature and size of potential hazards, their frequency of occurrence and their impact on a variety of elements at risk. As these judgements are based on the knowledge, experience and understanding of the assessor, it is not unusual for different assessors to make different judgements about the level of risk.

The thought process used in establishing likelihoods, consequences and determining spatial and temporal factors for properties at Muriwai has been documented for transparency. It is important to recognise the inherent imprecisions associated with the risk assessment process given the limitations of the inputs outlined above. Generally, the levels of likelihoods and risks should be thought of as being within a range of typically +/- half an order of magnitude at best.

While the basis for the judgements contained in this report are well documented, and the levels of risk considered to be good representations of reality, the accuracy and precision of the process should not be overestimated and should always be used in an appropriate manner in combination with risk management including mitigation and treatment options.

E2.5 Hazard Characterisation

E2.5.1 Landslide Hazards

AGS (2007c) generally states that all credible hazards originating on, above and below the sites should be assessed. This is generally a predictive exercise based on knowledge and understanding of the geological and geomorphological setting with a view to assembling historical evidence for past hazard events.

As noted above, the risk assessment presented in this report is limited to the assessment of risks posed by 'large scale' landslide hazards originating from the main escarpment located to the south-east of Muriwai. Smaller, more localised landslide hazards that could originate (or may have already initiated) from other areas in Muriwai such as small slips within the footprint of individual properties are not considered in this report, unless they have caused widespread damage.

The Appendix B report provides a detailed description of the landslide hazards at the site. The following summary provides an overview of the February 2023 landslides for context in this report.

Based on the GHD mapping and observations, the majority of the landslides[4] originating from the main escarpment comprised an initial translational failure. These failures were typically quite shallow, often in the order of 0.5 m to 1 m deep. Following initial failure, many of the landslide masses developed into rapid debris flows travelling various distances downslope, with some debris crossing Domain Crescent and Motutara Road.

In the southern part of the escarpment (i.e. Geomorphological Zone 3 as defined in the Appendix B report) the debris flows are typically more channelised flows, being somewhat confined by topographic features such as gullies. While this also occurs in the northern parts of the escarpment (i.e. Geomorphological Zone 2), these features are less prevalent in that zone, and the debris flows are commonly broader.

The width of the mapped landslide main (head) scarps / landslide crowns ranges from about 10 m to in excess of 50 m across the main escarpment. The width of the zone of deposited debris at the toe of each landslide varies depending on the extent of channelisation, with some landslide debris spreading out and increasing while in other areas the debris becomes more confined and narrows. The mapped landslides have estimated volumes ranging in the order from tens to thousands of cubic metres.

The landslide hazards considered as part of this assessment are as follows:

- **LS1a** (Landslide Hazard 1a): Landslides originating from the upper sections of the main escarpment that subsequently form debris flows that travel towards houses / dwellings located on or at the toe of the escarpment. This hazard is representative of the extensive landsliding that occurred across the escarpment in February 2023. This hazard affects areas of the site in the 'predicted modelled debris runout zone' as defined in Section 2.5.2.1.
- **LS1b** (Landslide Hazard 1b): Hazard as described in LS1a above however a more conservative (i.e. longer) modelled landslide runout zone has been adopted (See Section 2.5.2.1 below).
- **LS2a** (Landslide Hazard 2a): Landslides originating from the upper sections of the main escarpment that subsequently form debris flows that travel towards houses / dwellings located on or at the toe of the escarpment that are more frequent but less damaging than LS1a. This hazard is analogous to the more localised landsliding that occurred during the 1965 landslide event.
- **LS2b** (Landslide Hazard 2b): Hazard as described in LS2a above however a more conservative (i.e. longer) modelled landslide runout zone has been adopted (See Section 2.5.2.1 below).

E2.5.2 Landslide runout

The landslide runout was assessed using numerical modelling methods discussed below. The dwellings that have been assessed to be in the path of landslide runout are considered as the elements at risk for this assessment. The risks posed to individuals in the 'open', such as people outside houses or situated on other public property such as roads, are not considered in this report.

---

[4] Landslide terminology used in this report generally follows the scheme proposed by Cruden & Varnes (1996).

2.5.2.1 RAMMS debris flow modelling

The ‘RAMMS:Debrisflow module’ (RAMMS) was used to assess landslide runout and the spatial extent of areas potentially affected by landsliding. RAMMS is a numerical software package developed by the WSL Institute for Snow and Avalanche Research and is used to simulate the runout of debris-laden flows in complex terrain. The modelled landslide runout zones are referred to in this report as the ‘Predicted modelled debris runout zone’. This assessment is discussed in the Muriwai RAMMS debris flow analysis report in Appendix D.

The risk assessment presented in this report has relied on the outputs of the RAMMS modelling as the basis for determining areas of the site that could be affected by landsliding. The predicted modelled debris runout zones are presented in Figures A206 to A209 in Appendix A.

2.5.2.2 Empirical landslide runout assessment

Empirical methods have been used to further compare the landslide runout distances predicted using RAMMS and the observed landslide runouts. The empirical methods typically predicted a similar landslide runout to the observed landslide runouts This assessment is discussed in the Appendix B report.

E2.6 Likelihood of landsliding ($P_{(H)}$)

E2.6.1 Rainfall and relationship to landsliding

Council provided GHD with an assessment of available rainfall data associated with Cyclone Gabrielle (Auckland Council 2023) (AC memo). During Cyclone Gabrielle, the tipping bucket rain gauge at Muriwai failed and was inundated by flood waters. The AC memo also provided rainfall analysis using AC’s Quantitative Precipitation Estimate (QPE) Rain Radar System, which is a real-time rainfall product that utilises the MetService radar. The rainfall data presented by AC indicates a peak rainfall total for Muriwai during the event of 146.9 mm, occurring over 12-hour period. This total is more than the 100-year event at a 12-hour duration. The data suggests that for the 12-hour duration rainfall, the Annual Recurrence Interval (ARI) is more than 100 years and may be in the order of 250 years. However, we understand that the calculation above the 100-year assessment becomes increasingly unreliable, primarily as a result of the relatively short statistical rainfall records available in New Zealand. For the other durations modelled, the rainfall was below the 100-year event.

The AC memo recommended that an envelope of “risk” is estimated as the ARI figures will change over time as these events are incorporated into the statistical record. The AC memo states that, in general, it is considered reasonable to consider the Cyclone Gabrielle event to be in the range of 100 to 250 year ARI. For this assessment we have assumed that the annual likelihood of a landslide event occurring that is similar in magnitude to the February 2023 event, is about 1 in 100 (i.e., 0.01). This is considered to have a *likely* probability of occurrence as per AGS (2007c) Appendix C criteria.

The assumption of 1 in 100 based on rainfall frequency is a simplifying and possibly conservative assumption that we consider reasonable. It does not consider other factors that could potentially affect stability (antecedent conditions, geology, groundwater conditions, slope height and angle, vegetation, surface water management-overland flow path, overflow from water storage tanks, effect of effluent disposal field), all of which are difficult to quantify.

Based on discussions with AC, we understand that no reliable storm ARI value is available for the 1965 landslide event due to the lack of data. Hayward (2022) states that the 1965 landslides followed 2 days of unusually heavy rain, with a nearby gauge recording 95 mm on August 25 to 26, plus 45 mm in the 12 hours preceding the landslides that occurred on August 27, 1965. However, the author goes on to mention that this is somewhat less than that recorded officially for the 3-day period at Whenuapai (220 mm) and Manukau Heads (190 mm). Review of publicly available NIWA rainfall data suggests the ARI for a 3-day rainfall event of similar magnitude is less than 100. Considering the 1965 landslide event affected a considerably smaller area of the Muriwai escarpment than the recent 2023 event, suggests that the triggering rainfall event was smaller. Given the uncertainties above, we have assumed that a rainfall event with an ARI of about 50, could trigger a similar landslide event to that experienced in 1965.

The AC memo further recommended that risk assessment reports consider the potential for climate change to increase the frequency of high intensity rainfall. We understand that the National Institute of Water and

Atmospheric Research (NIWA) has projected a 20% increase in rainfall intensity over the next 100 years which suggests that a 250-year ARI event could increase to a 50-year ARI event. Consequently, we have also included sensitivity checks using more frequent ARI values as discussed in Section E2.6.2.

E2.6.2 Partitioning of likelihood

The rainfall events discussed in Section E2.6.1, the estimation of recurrence intervals for those events and the occurrence of the observed hazards, form the basis for the estimated probability of occurrence for the landslide hazards. However, observations of the recent and past events noted that not all similar slopes failed as a result of the initiating storm event and as such, additional considerations for probability of occurrence have been included within the analysis by using conditional probabilities as follows:

$$P_{(H)} = P_{(H'1)} \times P_{(H'2)}$$

Where:

> $P_{(H'1)}$ = Probability that the rainfall threshold for the landslide hazard is exceeded, which is taken as a proxy for landslide initiation. This is assumed to be 1 in 100 or 0.01 for LS1a and LS1b (see Section E2.6.1) or 1 in 50 or 0.02 under the influence of future climate change. For LS2a and LS2b, $P_{(H'1)}$ is assumed to be 1 in 50 or 0.02. Under the influence of future climate change we have assumed the ARI for the same event will be twice as likely (i.e. an ARI 100 event becomes an ARI 50 event).
>
> $P_{(H'2)}$ = Probability that the slope for the specific assessment fails, which we relate to the proportion of the area of actual failed slopes out of the total area of all slopes present. This probability is based on a spatial analysis of the total area of failed landslides slopes compared to the total area of all slopes in each of the geomorphological zones defined in the Appendix B report. The adopted $P_{(H'2)}$ values for LS1a and LS1b are presented in Table E4.

Geomorphological Zones 1 and 6 have both been assigned likelihood values that differ from those of other geomorphological zones. As discussed in the Appendix B report, no landslides were triggered in Zone 1 and only relatively localised small-scale landslides with limited runout were triggered in Zone 6. However, historical landslide headscarp features are apparent in the LiDAR data across these areas and we interpret this to mean that these areas are susceptible to large, potentially damaging landslides, especially in future storm events that are larger than Cyclone Gabrielle. On this basis, we consider a $P_{(H'2)}$ value that is greater than zero for the $P_{(H'1)}$ 0.01 (i.e. 1 in 100-year storm) event. Given there were either no or very limited landslides observed in these zones in February 2023, we have adopted a $P_{(H'2)}$ value of 0.01. There is no basis for estimating the potential for landslides during less frequent, more intense storms, i.e. a 1 in 1000-year storm ($P_{(H'1)}$ of 0.001).

For Zones 2, 3 and 4 the adopted $P_{(H'2)}$ value for LS2a / LS21b is 0.02 based on spatial analysis of historical mapping of the 1965 landslide area.

Table E4 Summary of adopted $P_{(H'2)}$ factors for LS1a and LS1b

Geomorphological zone	$P_{(H'2)}$
1	0.01
2	0.29
3	0.07
4	0.56
5	0.06
6	0.01

E2.7 Probability of spatial impact ($P_{(S:H)}$)

E2.7.1 Landslide upslope of dwelling

The AGS definition of spatial probability is represented by single term $P_{(S:H)}$ and is described as the probability of spatial impact by the landslide on the element at risk, given the landslide occurs and taking into account the travel direction and travel distance or reach.

For areas of the site located within the predicted modelled debris runout zones (LS1a, LS2a), $P_{(S:H)} = 1$.

For areas of the site located within the conservative modelled debris runout zones (LS1b, LS2b), we have assumed that $P_{(S:H)}$ is about one order of magnitude lower (i.e. about a 10% probability of exceeding the predicted modelled debris runout zones). $P_{(S:H)}$ is therefore = 0.1.

E2.7.2 Landslide below dwelling

Landslides below dwellings are not considered in this study as all landslides occurred on the escarpment, upslope of the dwellings, which are located at the toe of the slope. Dwellings at the top of the escarpment (i.e. on the west side of Oaia Road) that could be undermined by the regression of the escarpment edge in future landslide events are reported in a separate, future study.

E2.8 Temporal probability ($P_{(T:S)}$)

This assessment has not considered specific occupancy scenarios for each individual dwelling. We acknowledge that the occupancy of each dwelling could vary significantly depending on the demographics of the residents and the usage of the dwelling. For example, some may be predominantly used as holiday accommodation, occupied mainly on weekends, whereas others could be permanently occupied by working families. For risk assessments conducted at this scale, and given potential future planning decisions, it is typically not appropriate to consider unique occupancy scenarios because the usage of each dwelling will likely change each time the ownership of the property changes.

We have not considered the possibility that individuals could evacuate before the landslide event occurs as the landslide history at Muriwai suggests landslides occur rapidly with few obvious signs of failure prior to the event occurring. It is also not reasonable to expect individuals to be aware of potential landsliding should the rainfall triggering event occur during the night.

This assessment has assumed the following occupancies:

- Dwellings are typically occupied for 15 hours each day during weekdays;
- On weekends, dwellings are occupied for about 20 hours each day;

The percentage of time a dwelling is occupied is therefore about 68%.

Any further delineations of the spatial variations in occupancy (i.e. if a bedroom is at the front or the rear of the house etc) are not considered feasible or warranted within the context of the precision of this assessment.

E2.9 Vulnerability ($V_{(D:T)}$)

AGS (2007c, Appendix F) includes a table of vulnerability values for various inundation and building damage scenarios as adapted by Finlay et al (1999). It is important to note that the AGS (2007c) vulnerability table does not adequately cater for all the building damage scenarios GHD has observed in the Waitakere area. GHD has therefore further adapted this table and combined it with information from the TfNSW Guide to Slope Risk Analysis (2014) as well as observations of damage to buildings and structures resulting from the recent landslides in the Waitakere area (Table E5).

These values have been used as a guide and expert judgement has been applied to select a value within the range of values where appropriate.

Table E5 Summary of vulnerability values adopted for the Waitakere area

Case	Range	Typical value used in assessments	Comments
Person in a building that collapses under impact from debris flow	0.8 -1.0	0.9	Death is almost certain. Evacuation unlikely to occur
If building is inundated with debris and the person is buried	0.8 -1.0	0.8	Very high potential for death Evacuation unlikely to occur
If building is inundated with debris but no collapse occurs and the person is not buried	0.01 -0.1	0.1	High chance of survival Evacuation unlikely to occur
If the debris strikes the building only	0.001-0.05	0.01	High chance of survival

Most dwellings constructed below the escarpment at Muriwai comprise timber frame structures with various forms of lightweight cladding such as weatherboard and fibre cement. The extent of damage to dwellings varied considerably depending on where each was located with respect to the path of each landslide. During the mapping and reconnaissance visits undertaken by GHD it was commonly observed that total destruction occurred to the structure when the flow height of the landslide exceeded approximately 0.5 m. Figure E2 presents an example of a dwelling that was completely destroyed, sadly resulting in two fatalities. It is important to note that total destruction also occurred to many other dwellings in Muriwai that had already been evacuated. Had evacuation not occurred the survivability in many of these properties would have been very low.

As discussed in the Appendix B report, the 1965 Muriwai landslides destroyed two dwellings, killing two of four people who were occupying one of the houses. One house was completely destroyed by the landslide and collapsed while the other was “swept off its foundation” and carried across Domain Crescent where it came to rest surrounded by debris (Hayward 2022).

In many observed instances trees entrained in the landslide mass played a large role in the destruction of dwellings in the 2023 event (Figure E4 to Figure E7). Accumulations of trees and other vegetation were commonly rafted and entrained towards the top of each slide mass which subsequently impacted the upslope side of dwellings. The thickness of these accumulated piles of vegetation debris sometimes exceeded 3 m. It is clear that the direct impact effects of the vegetation piles into dwellings were responsible for extensive damage and complete destruction in a number of circumstances.

Figure E2 *Example of a dwelling completely destroyed on Motutara Road where two fatalities occurred.*

Figure E3 *View of same dwelling pictured in Figure E2 showing overall view of landslide with accumulated vegetation at toe of slide.*

Figure E4 *Example of a dwelling on Domain Crescent completely destroyed by landslide with large pile of accumulated vegetation debris on upslope side.*

Figure E5 *View of upslope side of completely destroyed timber frame dwelling. Note large pile of accumulated vegetation debris on left.*

Figure E6 *View of the same dwelling pictured in Figure E5 taken further upslope. Note mixture of soil debris and vegetation. Residence has been moved several metres downslope.*

Figure E7 *View of remains of completely destroyed house on slope above Motutara Road. Note mixture of soil debris and vegetation.*

The observations of building damage at Muriwai are in good agreement with a study by Kang et al. (2016) that compared physical vulnerability of different types of building structures to debris flow events. In this context, physical vulnerability is a representation of the expected degree of loss and is quantified on a scale of 0 (no damage) to 1 (total destruction) (Fell et al. 2005). This should not be confused with the vulnerability to individuals (probability of loss of life of the individual given the impact). Kang et al. (2016) developed a number of vulnerability curves using the degree of damage to buildings coupled with intensities of the debris flow events (Figure E8).

The Kang et al. (2016) vulnerability curves for both flow depth and velocity typically are in good agreement with the Muriwai observations and modelling. For example, total destruction of a timber frame structure becomes increasingly likely as the flow depth approaches 1 m thickness.

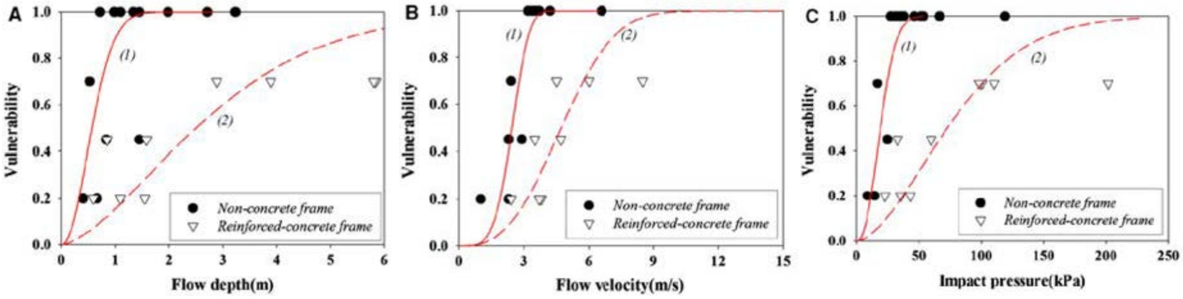


Figure E8 ***Debris flow vulnerability (physical vulnerability) curves as a function of the flow depth, flow velocity, and impact pressure (Kang 2016).***

Despite the total destruction of many houses in Muriwai, a number of houses were impacted by more than 0.5 m thickness of debris and associated vegetation and were not completely destroyed. For example, Figure E9 to Figure E11 shows a two-storey dwelling on Domain Crescent that toppled over, leaving the upper storey largely intact. The ground floor of the structure has completely collapsed and is inundated with debris. In this example, had individuals been present on the ground floor it is unlikely they would have survived. However, the survivability on the upper floor is assessed to be relatively high, perhaps only leading to injuries should individuals have been present. This example demonstrates the challenges of adopting a representative vulnerability value for individuals occupying a single dwelling.

Figure E12 and Figure E13 present another example of a two-storey timber frame house impacted by a landslide. The dwelling has deformed as is evident by the tilting of walls and distortion of door frames, but the structure is largely intact, and no inundation appears to have occurred. The survivability from this damage is also considered to be very high.

There are many factors that could have contributed to some houses experiencing significantly less damage than others, despite the reasons not being immediately obvious based on observations alone. For example, the flow velocity in some instances may have been very low by the time the distal end of the flow reached a house. Alternatively, the construction methods of some houses may be more resistant to landslide impacts than others. Given these uncertainties it is not reasonable or practical to assign unique vulnerability values to different dwellings at the site.

Figure E9 *Example of a dwelling on Domain Crescent where ground floor of the structure has collapsed causing house to topple over with the upper storey remaining largely intact.*

Figure E10 *View of side profile of dwelling pictured in Figure E9, showing collapse of the ground floor and build-up of vegetation debris at rear.*

Figure E11 Aerial view of dwelling pictured in Figure E10. The debris flow originated at the far right of the photo.

Figure E12 Side view of home above Motutara Road. Note tilting of upper storey wall and deformed window frame.

Figure E13 View of upslope side of dwelling pictured in Figure E12 showing accumulated landslide debris against rear wall.

Table E6 presents a summary of the adopted vulnerability probability factors used in this assessment.

Table E6 Summary of adopted vulnerability probability factors

Hazard	Vulnerability ($V_{(D:T)}$)	Comments
LS1a	0.8	Building is likely to be inundated and may collapse. Very high potential for death. Evacuation unlikely to occur. Since 1965, four fatalities have occurred at Muriwai where building collapse has occurred.
LS1b	0.8	Building is likely to be inundated and may collapse. Very high potential for death. Evacuation unlikely to occur. Since 1965, four fatalities have occurred at Muriwai where building collapse has occurred.
LS2a	0.8	Building is likely to be inundated and may collapse. Very high potential for death. Evacuation unlikely to occur. Since 1965, four fatalities have occurred at Muriwai where building collapse has occurred.
LS2b	0.8	Building is likely to be inundated and may collapse. Very high potential for death. Evacuation unlikely to occur. Since 1965, four fatalities have occurred at Muriwai where building collapse has occurred.

E2.10 Risk estimation

A summary of the risk estimation for each Geomorphological Zone is presented in Table E7 below. A sensitivity check assuming a higher probability of occurrence for $P_{(H)}$ is included for comparative purposes. As can be seen, this increases the risk and, in some cases in Zones 1 and 6, changes the risk evaluation.

Table E7 *Summary of risk estimation for each hazard type by Geomorphological Zone*

Geomorphological Zone	Hazard	Description	Annual probability of the landslide P$_{(H)}$		Spatial probability	Temporal probability	Vulnerability	Risk	Risk Evaluation*
			P$_{(H'1)}$	P$_{(H'2)}$	P$_{(S:H)}$	P$_{(T:S)}$	V$_{(D:T)}$	R$_{(LOL)}$	
1	LS1a	Debris Flow upslope of dwelling	0.010	0.01	1.00	0.68	0.80	5.4 x 10^{-5}	Tolerable
	LS1a	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.01*	*1.00*	*0.68*	*0.80*	*1.1 x 10^{-4}*	*Not tolerable*
	LS1b	Debris Flow upslope of dwelling (longer modelled runout)	0.010	0.01	0.10	0.68	0.80	5.4 x 10^{-6}	Acceptable
	LS1b	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.01*	*0.10*	*0.68*	*0.80*	*1.1 x 10^{-5}*	*Tolerable*
	LS2a	Debris Flow upslope of dwelling (more frequent, less widespread)	0.010	0.01	1.00	0.68	0.80	5.4 x 10^{-5}	Tolerable
	LS2a	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.01*	*1.00*	*0.68*	*0.80*	*1.1 x 10^{-4}*	*Not tolerable*
	LS2b	Debris Flow upslope of dwelling (more frequent, less widespread with longer modelled runout)	0.010	0.01	0.10	0.68	0.80	5.4 x 10^{-6}	Acceptable
	LS2b	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.01*	*0.10*	*0.68*	*0.80*	*1.1 x 10^{-5}*	*Tolerable*
2	LS1a	Debris Flow upslope of dwelling	0.010	0.29	1.00	0.68	0.80	1.6 x 10^{-3}	Not tolerable
	LS1a	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.29*	*1.00*	*0.68*	*0.80*	*3.2 x 10^{-3}*	*Not tolerable*
	LS1b	Debris Flow upslope of dwelling (longer modelled runout)	0.010	0.29	0.10	0.68	0.80	1.6 x 10^{-4}	Not tolerable
	LS1b	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.29*	*0.10*	*0.68*	*0.80*	*3.2 x 10^{-4}*	*Not tolerable*
	LS2a	Debris Flow upslope of dwelling (more frequent, less widespread)	0.020	0.02	1.00	0.68	0.80	2.2 x 10^{-4}	Not tolerable
	LS2a	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.040*	*0.02*	*1.00*	*0.68*	*0.80*	*4.4 x 10^{-4}*	*Not tolerable*
	LS2b	Debris Flow upslope of dwelling (more frequent, less widespread with longer modelled runout)	0.020	0.02	0.10	0.68	0.80	2.2 x 10^{-5}	Tolerable
	LS2b	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.040*	*0.02*	*0.10*	*0.68*	*0.80*	*4.4 x 10^{-5}*	*Tolerable*
3	LS1a	Debris Flow upslope of dwelling	0.010	0.07	1.00	0.68	0.80	3.8 x 10^{-4}	Not tolerable
	LS1a	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.07*	*1.00*	*0.68*	*0.80*	*7.6 x 10^{-4}*	*Not tolerable*
	LS1b	Debris Flow upslope of dwelling (longer modelled runout)	0.010	0.07	0.10	0.68	0.80	3.8 x 10^{-5}	Tolerable
	LS1b	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.07*	*0.10*	*0.68*	*0.80*	*7.6 x 10^{-5}*	*Tolerable*
	LS2a	Debris Flow upslope of dwelling (more frequent, less widespread)	0.020	0.02	1.00	0.68	0.80	2.2 x 10^{-4}	Not tolerable
	LS2a	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.040*	*0.02*	*1.00*	*0.68*	*0.80*	*4.4 x 10^{-4}*	*Not tolerable*
	LS2b	Debris Flow upslope of dwelling (more frequent, less widespread with longer modelled runout)	0.020	0.02	0.10	0.68	0.80	2.2 x 10^{-5}	Tolerable

Geomorphological Zone	Hazard	Description	Annual probability of the landslide $P_{(H)}$		Spatial probability	Temporal probability	Vulnerability	Risk	Risk Evaluation*
			$P_{(H'1)}$	$P_{(H'2)}$	$P_{(S:H)}$	$P_{(T:S)}$	$V_{(D:T)}$	$R_{(LOL)}$	
	LS2b	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.040*	*0.02*	*0.10*	*0.68*	*0.80*	*4.4 x 10^{-5}*	*Tolerable*
4	LS1a	Debris Flow upslope of dwelling	0.010	0.56	1.00	0.68	0.80	3.0 x 10^{-3}	Not tolerable
	LS1a	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.56*	*1.00*	*0.68*	*0.80*	*6.1 x 10^{-3}*	*Not tolerable*
	LS1b	Debris Flow upslope of dwelling (longer modelled runout)	0.010	0.56	0.10	0.68	0.80	3.0 x 10^{-4}	Not tolerable
	LS1b	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.56*	*0.10*	*0.68*	*0.80*	*6.1 x 10^{-4}*	*Not tolerable*
	LS2a	Debris Flow upslope of dwelling (more frequent, less widespread)	0.020	0.02	1.00	0.68	0.80	2.2 x 10^{-4}	Not tolerable
	LS2a	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.040*	*0.02*	*1.00*	*0.68*	*0.80*	*4.4 x 10^{-4}*	*Not tolerable*
	LS2b	Debris Flow upslope of dwelling (more frequent, less widespread with longer modelled runout)	0.020	0.02	0.10	0.68	0.80	2.2 x 10^{-5}	Tolerable
	LS2b	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.040*	*0.02*	*0.10*	*0.68*	*0.80*	*4.4 x 10^{-5}*	*Tolerable*
5	LS1a	Debris Flow upslope of dwelling	0.010	0.06	1.00	0.68	0.80	3.3 x 10^{-4}	Not tolerable
	LS1a	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.06*	*1.00*	*0.68*	*0.80*	*6.5 x 10^{-4}*	*Not tolerable*
	LS1b	Debris Flow upslope of dwelling (longer modelled runout)	0.010	0.06	0.10	0.68	0.80	3.3 x 10^{-5}	Tolerable
	LS1b	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.06*	*0.10*	*0.68*	*0.80*	*6.5 x 10^{-5}*	*Tolerable*
	LS2a	Debris Flow upslope of dwelling (more frequent, less widespread)	0.020	0.02	1.00	0.68	0.80	2.2 x 10^{-4}	Not tolerable
	LS2a	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.040*	*0.02*	*1.00*	*0.68*	*0.80*	*4.4 x 10^{-4}*	*Not tolerable*
	LS2b	Debris Flow upslope of dwelling (more frequent, less widespread with longer modelled runout)	0.020	0.02	0.10	0.68	0.80	2.2 x 10^{-5}	Tolerable
	LS2b	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.040*	*0.02*	*0.10*	*0.68*	*0.80*	*4.4 x 10^{-5}*	*Tolerable*
6	LS1a	Debris Flow upslope of dwelling	0.010	0.01	1.00	0.68	0.80	5.4 x 10^{-5}	Tolerable
	LS1a	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.01*	*1.00*	*0.68*	*0.80*	*1.1 x 10^{-4}*	*Not tolerable*
	LS1b	Debris Flow upslope of dwelling (longer modelled runout)	0.010	0.01	0.10	0.68	0.80	5.4 x 10^{-6}	Acceptable
	LS1b	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.01*	*0.10*	*0.68*	*0.80*	*1.1 x 10^{-5}*	*Tolerable*
	LS2a	Debris Flow upslope of dwelling (more frequent, less widespread)	0.010	0.01	1.00	0.68	0.80	5.4 x 10^{-5}	Tolerable
	LS2a	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.01*	*1.00*	*0.68*	*0.80*	*1.1 x 10^{-4}*	*Not tolerable*
	LS2b	Debris Flow upslope of dwelling (more frequent, less widespread with longer modelled runout)	0.010	0.01	0.10	0.68	0.80	5.4 x 10^{-6}	Acceptable

Geomorphological Zone	**Hazard**	**Description**	**Annual probability of the landslide $P_{(H)}$**		**Spatial probability**	**Temporal probability**	**Vulnerability**	**Risk**	**Risk Evaluation***
			$P_{(H'1)}$	$P_{(H'2)}$	$P_{(S:H)}$	$P_{(T:S)}$	$V_{(D:T)}$	$R_{(LOL)}$	
	LS2b	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.01*	*0.10*	*0.68*	*0.80*	*1.1×10^{-5}*	*Tolerable*

***The evaluation is a guide only based on recommendations from AGS (2007) which provides a suggested tolerable annual Loss of Life Risk for the person most at risk (existing slopes) is 1 x 10^{-4} (1 in 10,000).**

E3. Conclusions

The travel paths for the assessed landslide hazards are based on the ‘predicted modelled debris runout zone’ as discussed in Section E2.5 (see Figures A206 to A209 in Appendix A). The estimated risks presented in this report for debris flow hazards only apply to areas of the site located within these zones. A summary of the estimated risks is presented below.

We emphasise that this evaluation is a guide only based on recommendations from AGS (2007) which provides a suggested tolerable Loss of Life Risk for the person most at risk (existing slopes).

E3.1 Loss of life risk from debris flow

E3.1.1 Geomorphological Zone 1

With regards to the LS1a hazard, these risks have been assessed to be tolerable according to the evaluation against the AGS (2007c) suggested tolerable Loss of Life Risk limit for the person most at risk. The risk associated with LS2a has also been estimated to be below the AGS (2007c) suggested tolerable Loss of Life Risk limit. Using a higher likelihood related to climate change for each of these cases would result in higher levels of risk evaluated as not tolerable against the AGS (2007c) recommended criteria (see Table E3).

Table E8 Summary of risk estimation, Zone 1

Geomorphological Zone	Hazard	Description	Risk Evaluation
1	LS1a	Debris Flow upslope of dwelling	Tolerable
	LS1b	Debris Flow upslope of dwelling (longer modelled runout)	Acceptable
	LS2a	Debris Flow upslope of dwelling (more frequent, less widespread)	Tolerable
	LS2b	Debris Flow upslope of dwelling (more frequent, less widespread with longer modelled runout)	Tolerable

E3.1.2 Geomorphological Zone 2

With regards to hazards LS1a, LS1b and LS2a, we have estimated these risks to **exceed** the AGS (2007c) suggested tolerable Loss of Life Risk for the person most at risk (Table E9). Using a higher likelihood related to climate change for each of these cases also results in higher levels of risk evaluated as not tolerable against the AGS (2007c) recommended criteria (see Table E3).

Table E9 Summary of risk estimation, Zone 2

Geomorphological Zone	Hazard	Description	Risk Evaluation
2	LS1a	Debris Flow upslope of dwelling	Not tolerable
	LS1b	Debris Flow upslope of dwelling (longer modelled runout)	Not tolerable
	LS2a	Debris Flow upslope of dwelling (more frequent, less widespread)	Not tolerable
	LS2b	Debris Flow upslope of dwelling (more frequent, less widespread with longer modelled runout)	Tolerable

E3.1.3 Geomorphological Zone 3

With regards to hazards LS1a and LS2a, we have estimated these risks to **exceed** the AGS (2007c) suggested tolerable Loss of Life Risk for the person most at risk (Table E10). Using a higher likelihood related to climate change for each of these cases also results in higher levels of risk evaluated as not tolerable against the AGS (2007c) recommended criteria (see Table E3).

Table E10 Summary of risk estimation, Zone 3

Geomorphological Zone	Hazard	Description	Risk Evaluation
3	LS1a	Debris Flow upslope of dwelling	Not tolerable
	LS1b	Debris Flow upslope of dwelling (longer modelled runout)	Tolerable
	LS2a	Debris Flow upslope of dwelling (more frequent, less widespread)	Not tolerable
	LS2b	Debris Flow upslope of dwelling (more frequent, less widespread with longer modelled runout)	Tolerable

E3.1.4 Geomorphological Zone 4

With regards to hazards LS1a, LS1b and LS2a, we have estimated these risks to **exceed** the AGS (2007c) suggested tolerable Loss of Life Risk for the person most at risk (Table E11). Using a higher likelihood related to climate change for each of these cases also results in higher levels of risk evaluated as not tolerable against the AGS (2007c) recommended criteria (see Table E3).

Table E11 Summary of risk estimation, Zone 4

Geomorphological Zone	Hazard	Description	Risk Evaluation*
4	LS1a	Debris Flow upslope of dwelling	Not tolerable
	LS1b	Debris Flow upslope of dwelling (longer modelled runout)	Not tolerable
	LS2a	Debris Flow upslope of dwelling (more frequent, less widespread)	Not tolerable
	LS2b	Debris Flow upslope of dwelling (more frequent, less widespread with longer modelled runout)	Tolerable

E3.1.5 Geomorphological Zone 5

With regards to hazards LS1a and LS2a, we have estimated these risks to **exceed** the AGS (2007c) suggested tolerable Loss of Life Risk for the person most at risk (Table E12). Using a higher likelihood related to climate change for each of these cases also results in higher levels of risk evaluated as not tolerable against the AGS (2007c) recommended criteria (see Table E3).

Table E12 Summary of risk estimation, Zone 5

Geomorphological Zone	Hazard	Description	Risk Evaluation
5	LS1a	Debris Flow upslope of dwelling	Not tolerable
	LS1b	Debris Flow upslope of dwelling (longer modelled runout)	Tolerable
	LS2a	Debris Flow upslope of dwelling (more frequent, less widespread)	Not tolerable
	LS2b	Debris Flow upslope of dwelling (more frequent, less widespread with longer modelled runout)	Tolerable

E3.1.6 Geomorphological Zone 6

With regards to the LS1a hazard, these risks have been assessed to be tolerable according to the evaluation against the AGS (2007c) suggested tolerable Loss of Life Risk limit for the person most at risk as presented in Table E13. The risk associated with LS2a has also been estimated to be below the AGS (2007c) suggested tolerable Loss of Life Risk limit. Using a higher likelihood related to climate change for each of these cases would result in higher levels of risk evaluated as not tolerable against the AGS (2007c) recommended criteria (see Table E3).

Table E13 Summary of risk estimation, Zone 6

Geomorphological Zone	Hazard	Description	Risk Evaluation
6	LS1a	Debris Flow upslope of dwelling	Tolerable
	LS1b	Debris Flow upslope of dwelling (longer modelled runout)	Acceptable
	LS2a	Debris Flow upslope of dwelling (more frequent, less widespread)	Tolerable
	LS2b	Debris Flow upslope of dwelling (more frequent, less widespread with longer modelled runout)	Tolerable

E3.2 Loss of life risk for 85 and 87 Domain Crescent and 207 Motutara Road

The unmitigated risk for 85 and 87 Domain Crescent in Zone 3 and 207 Motutara Road in Zone 2 is summarised in Table E14 (see Appendix E-2, E-3 and E-4 respectively).

Table E14 Summary of unmitigated risk estimation for 85 and 87 Domain Crescent and 207 Motutara Road, Muriwai

Hazard	Description	Risk Evaluation
LS1 – 85 Domain Crescent	Landslide upslope of dwelling	Not tolerable
LS1 – 87 Domain Crescent	Landslide upslope of dwelling	Not tolerable
LS1 – 207 Motutara Road	Landslide upslope of dwelling	Tolerable
LS2 – 207 Motutara Road	Regression of existing landslide	Not tolerable

E3.3 Closure

This report has presented the results of a quantitative risk assessment to estimate the risk of Loss of Life posed by large-scale landslides to individuals in dwellings at Muriwai. This assessment has only considered the 'large scale' landslide hazards originating from the main escarpment located to the south-east of Muriwai. This assessment has not considered risks to dwellings at the crest of the escarpment (i.e. along Oaia Road) that are susceptible to undermining due to regression of the escarpment.

We understand Council are currently reviewing their tolerable and acceptable risk criteria for risks associated with landsliding. We recommend Council review the risk assessment presented in this report against the Council's own risk criteria to inform decisions on future land planning, dwelling hazard designations and the revision of current building placards.

As discussed above, this report considers geotechnical matters only. There may be other non-geotechnical considerations that affect final placard designation of which GHD are not aware, such as flood risk and structural damage to property.

E4. References

AGS (2000). Landslide risk management concepts and guidelines. Australian Geomechanics Society. Australian Geomechanics Vol 35, No 1, 49-92

AGS (2002). Landslide risk management concepts and guidelines. Australian Geomechanics Society. Australian Geomechanics Vol 37, No 2, 1-44

AGS (2007a). Guideline for Landslide Susceptibility, Hazard and Risk Zoning for Land Use Management. Australian Geomechanics Society, Australian Geomechanics, Vol 42, No1.

AGS (2007b). Commentary on Guideline for Landslide Susceptibility, Hazard and Risk Zoning for Land Use Management, Australian Geomechanics Society, Australian Geomechanics, Vol 42, No1.

AGS (2007c). Practice Note Guidelines for Landslide Risk Management Australian Geomechanics Society. Australian Geomechanics, Vol 42, No1.

AGS (2007d). Commentary on Practice Note Guidelines for Landslide Risk Management. . Australian Geomechanics, Vol 42, No1.

Cruden D.M. & Varnes D. J. (1996). Landslide types and processes. In: Turner A.K.; Schuster R.L. (eds) Landslides: Investigation and Mitigation. Transportation Research Board, U.S. National Academy of Sciences, Special Report, 247: 36-75.

P J Finlay, G R Mostyn & R Fell (1999). ‘Landslides: Prediction of Travel Distance and Guidelines for Vulnerability of Persons’. Proc 8th. Australia New Zealand Conference on Geomechanics, Hobart. Australian Geomechanics Society, ISBN 1 86445 0029, Vol 1, pp.105-113.

Hayward, B., (2022). The tragic 1965 Muriwai Landslide. Geocene 28: 2-5

Heim, A. (1932). Landslides and human lives (Bergstruz and Menchen leben). Translated by N. Skermer. BiTech Publishers, Vancouver, B.C., 195 p

Hsu, K.J. (1975) Catastrophic debris streams (sturzstroms) generated by rockfalls. Geological Society of America Bulletin, Vol 86, pp. 129-140.

Kang, Hs., Kim, Yt. (2016) The physical vulnerability of different types of building structure to debris flow events. Nat Hazards 80, 1475–1493. https://doi.org/10.1007/s11069-015-2032-z

New South Wales Government, Transport for New South Wales ‘Guide to Slope Risk Analysis’ Version 4, April 2014.

E5. Limitations

This report has been prepared by GHD Limited (GHD) for Auckland Council and may only be used and relied on by Auckland Council for the purpose agreed between GHD and Auckland Council as set out in Section 1 of this report.

GHD otherwise disclaims responsibility to any person other than Auckland Council arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

The opinions, conclusions and any recommendations in this report are based on assumptions made by GHD described in this report (refer Section 1 of this report). GHD disclaims liability arising from any of the assumptions being incorrect.

GHD does not accept responsibility arising from, or in connection with, varied conditions and any change in conditions. GHD is also not responsible for updating this report if the conditions change.

An understanding of the geotechnical site conditions depends on the integration of many pieces of information, some regional, some site specific, some structure specific and some experienced based. Hence this report should not be altered, amended, abbreviated, or issued in part in any way without prior written approval by GHD. GHD does not accept liability in connection with the issuing of an unapproved or modified version of this report.

Verification of the geotechnical assumptions and/or model is an integral part of the design process - investigation, construction verification, and performance monitoring. If the revealed ground or groundwater conditions vary from those assumed or described in this report the matter should be referred back to GHD.

Appendices

Appendix E-1

AC flood frequency memo (20/09/2023)

Memo

20/09/2023

To: Debbie Fellows, Matt Howard

cc: Jin Lee, Nicole Li, Ross Roberts

From: Kris Fordham

Subject: **GUIDELINES ON THE USE OF AGS2007 FOR LANDSLIDE RISK ASSESSMENT IN AUCKLAND FOLLOWING THE 2023 FLOODING AND CYCLONE**

INTRODUCTION

It is anticipated that the use of the AGS2007 guidelines will form a core part of the risk assessment process for recovery in Auckland. This guidance has been developed to support practitioners in implementing the AGS guidelines by providing location and event specific information and advice, along with lessons learned from earlier implementations.

This guideline will be revised regularly as more information becomes available, and as new lessons are learned.

Risk assessment is expected to be undertaken on a site-specific basis. Nothing in this document relieves the person undertaking the risk assessment of their obligations to properly assess the conditions at each location and to make an assessment relevant to the site. These general guidelines may support this process, but deviation from the guidelines is to be expected where conditions dictate.

DERIVING PROBABILITY OF A LANDSLIDE OCCURRING

In the 2007 update of the AGS guidelines, it was noted that some practitioners were incorrectly deriving indicative probability values for risk to life analysis. The 2000 version Appendix G Likelihood table was being used from left to right; that is a descriptor was selected from the description (or even by preference for the descriptor), and then the indicative probability assigned accordingly. This method is wrong. The Likelihood Table was reordered to indicate the correct sequence of logic from left to right and as discussed in section C5.4.2, an estimate of the probability should be made based on apparent performance, trigger probabilities etc, and then the descriptor assigned accordingly.

The tables provided in Appendix C of AGS2007c should be used from left to right; use Approximate Annual Probability or Description to assign Descriptor, not vice versa.

GENERAL CONSIDERATIONS FOR RAINFALL ARI

Short-term vs Long-term risk

In many cases there will be a requirement to assess the short-term risk (for the purposes of RBA placarding and building occupation) and the long-term risk (for risk categorisation and consenting if remedial works are required).

Short-term considerations

Short-term risk (nominally 1 year) will not need to consider the potential for climate change to increase the frequency of high-intensity rainfall. However, consideration should be given to the extremely wet 2023 summer which has led to unusually high groundwater levels. This could mean that landslides are more likely than normal in smaller rainfall events.

Long-term considerations

Long-term risk (nominally 100 years) should consider the potential for climate change to increase the frequency of high intensity rainfall.

More information on this can be found:

- In a summary of Auckland climate projections prepared by NIWA (2018): **https://knowledgeauckland.org.nz/media/1171/tr2017-031-2-auckland-region-climate-change-projections-and-impacts-summary-revised-jan-2018.pdf**

- In a technical paper: **https://www.nzgs.org/libraries/climate-change-sustainable-development-and-geotechnical-engineering-a-new-zealand-framework-for-improvement/**

ASSESSING THE ARI OF THE CYCLONE GABRIELLE EVENT - MURIWAI

Based on the best available data from rain radar, the rain experienced during Cyclone Gabrielle in Muriwai was >100-year event at a 12-hour duration.

This was a significant event for the region which came off the back of a significant “wet” period, including the event on the 27th of January 2023.

In Muriwai there are two sources of rainfall data available for analysis.

1. Physical TB3 tipping bucket rain gauge.
2. Auckland Councils Quantitative Precipitation Estimate (QPE) Rain Radar System.

TB3 tipping bucket rain gauge.

Unfortunately, during Cyclone Gabrielle, the tipping bucket rain gauge at Muriwai failed and was inundated by flood waters. This event record presented below in **Figure** 1 is compromised as a result but provides an indication of the rainfall intensities at Muriwai prior to the site failing.
Prior to the gauge failing (01:15 am on the 14th), the gauge had recorded 129mm of rain with a peak 6-hour total of 88mm of rain, which is >20-year event (TP108, Auckland design rainfall depths).

Due to the missing record and the site being inundated during the event, this record is not recommended to be used to describe the event.

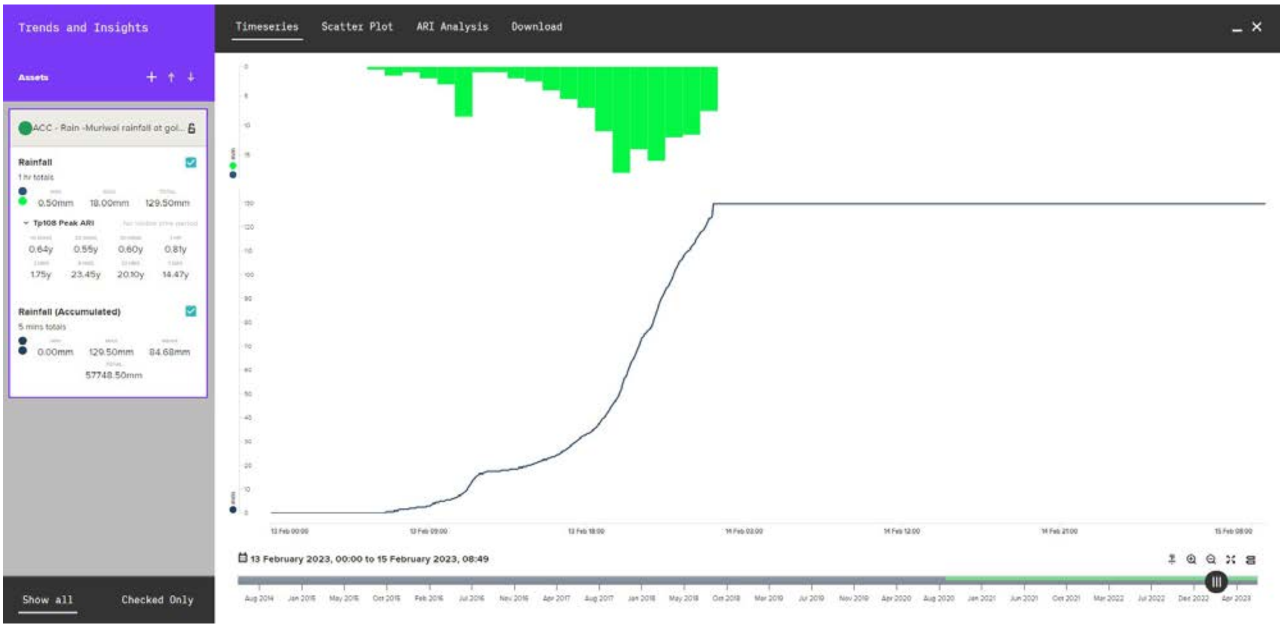
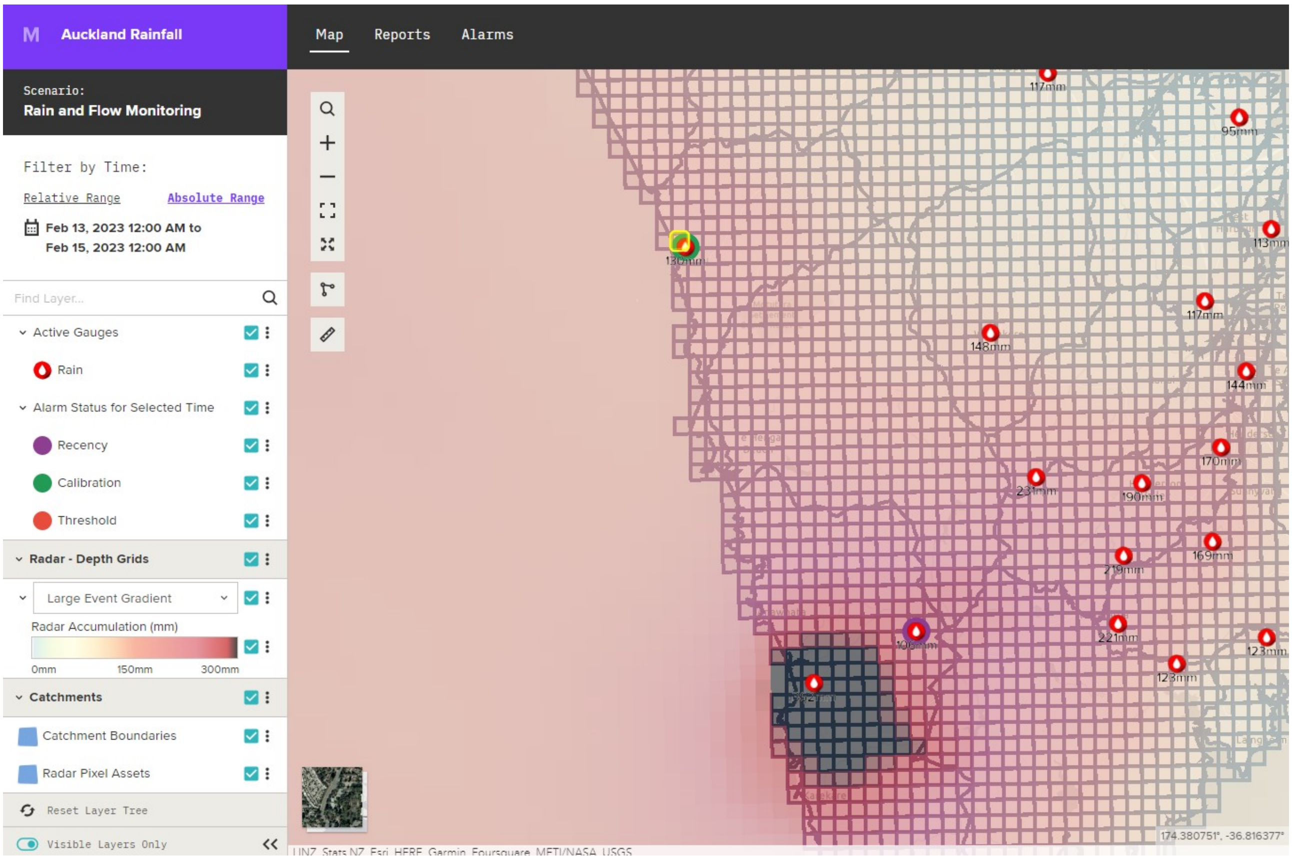


Figure 1: Muriwai TB3 tipping bucket rain gauge hourly totals and cumulative total. (note, the event is missing data from 01:15am 14th February due to being inundated)

Quantitative Precipitation Estimate (QPE) Rain Radar System.

The QPE rain radar system is a real-time rainfall product which utilises the Metservice radar (reflectivity), which is transformed using a relationship to rainfall depths based on the tipping bucket gauge network. The result is spatially representative rainfall depths across the region, as shown in **Figure 2**.

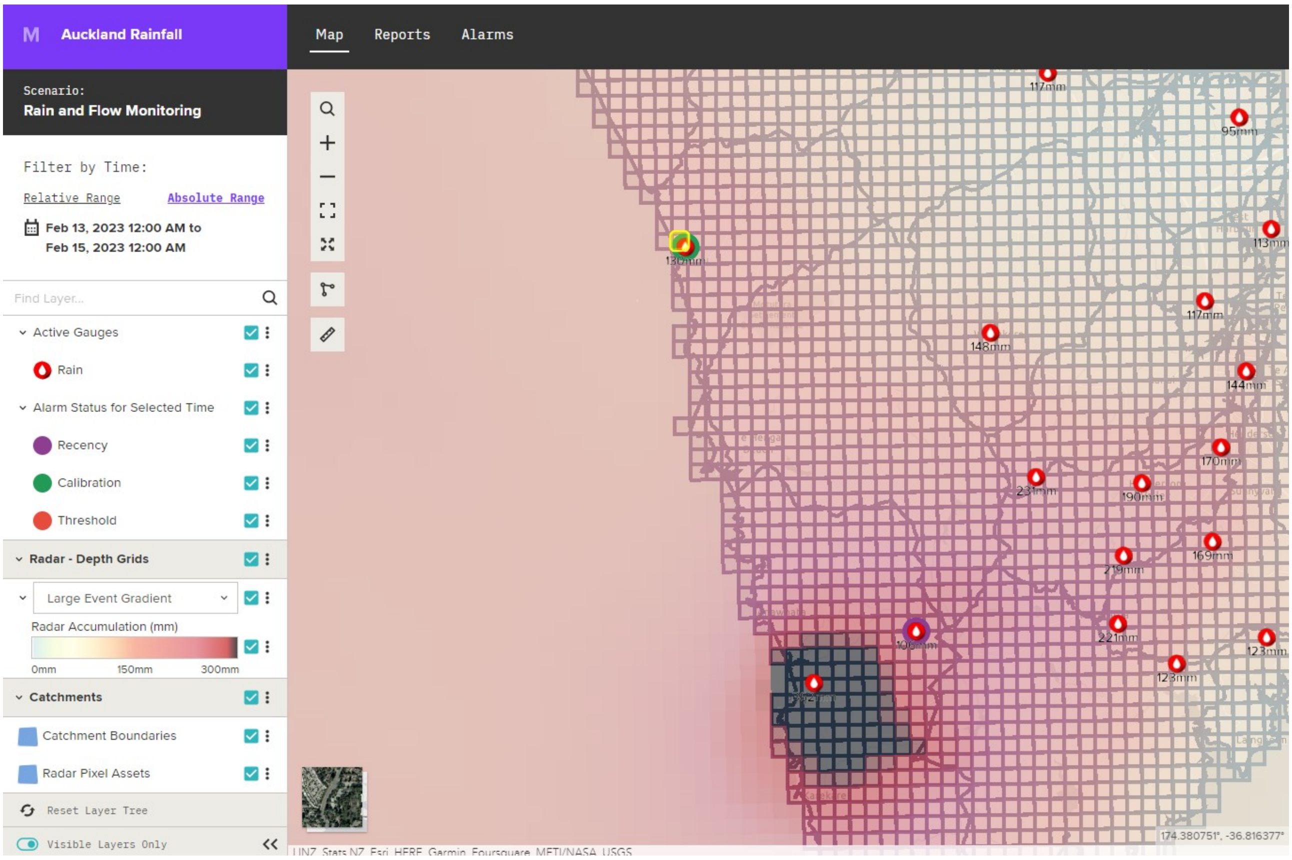
This product enables full, region wide analysis of extreme rainfall events in catchments where rain gauges are not located and when a gauge fails, as in the case with the Muriwai gauge.



Scenario:
Rain and Flow Monitoring

Filter by Time:
Relative Range Absolute Range
Feb 13, 2023 12:00 AM to
Feb 15, 2023 12:00 AM

Figure 2; QPE Rain radar depth accumulations 13 February 2023 to 15 February 2023. The yellow grid location is the rainfall at the raingauge location at Muriwai



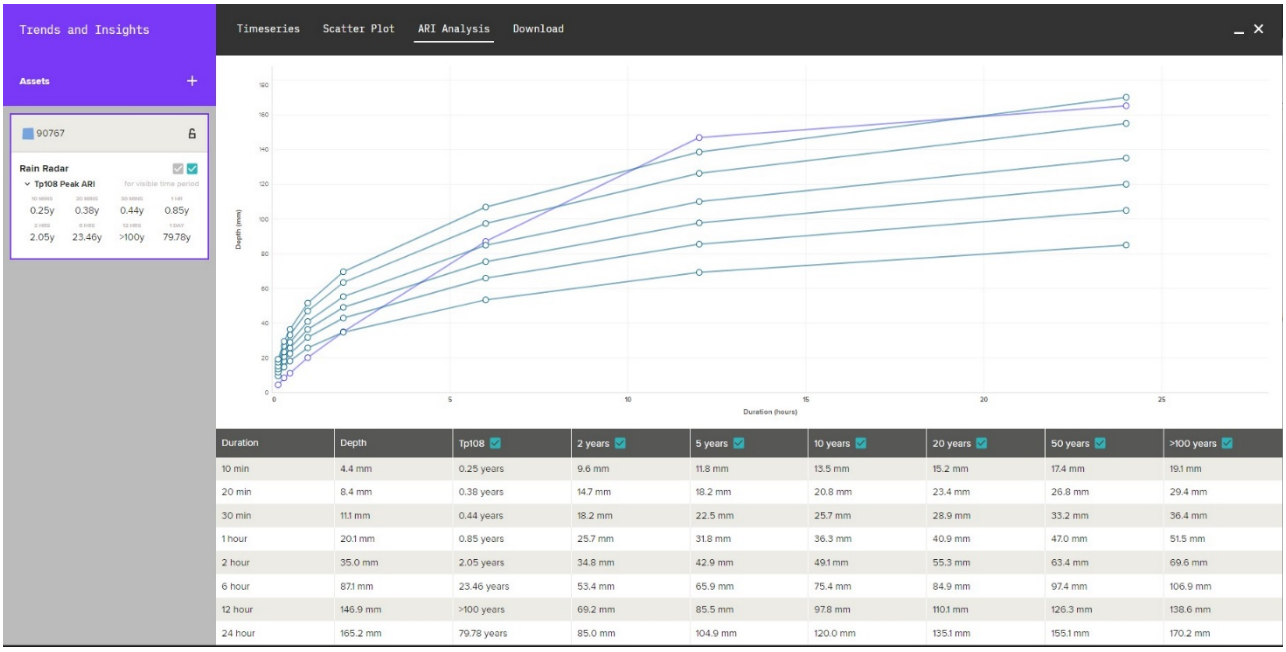
Scenario:
Rain and Flow Monitoring

Filter by Time:
Relative Range Absolute Range
Feb 13, 2023 12:00 AM to
Feb 15, 2023 12:00 AM

Figure 3: QPE Rain radar depths in Muriwai 13 February 2023 to 15 February 2023

Figure 4 below shows the Depth-duration-Frequency curve for the QPE grid location at Muriwai. The X-axis shows duration, y axis shows depth in a given event, and the curves show the expected rainfall depths for a range of ARIs from 2 to 100-year return period (TP108, Auckland design rainfall depths).

What happened during the event is plotted in purple. This analysis and the figures in table 1 shows that the peak rainfall total during the event of 146.9mm occurred over 12-hour period. This total is >100-year event at a 12-hour duration.



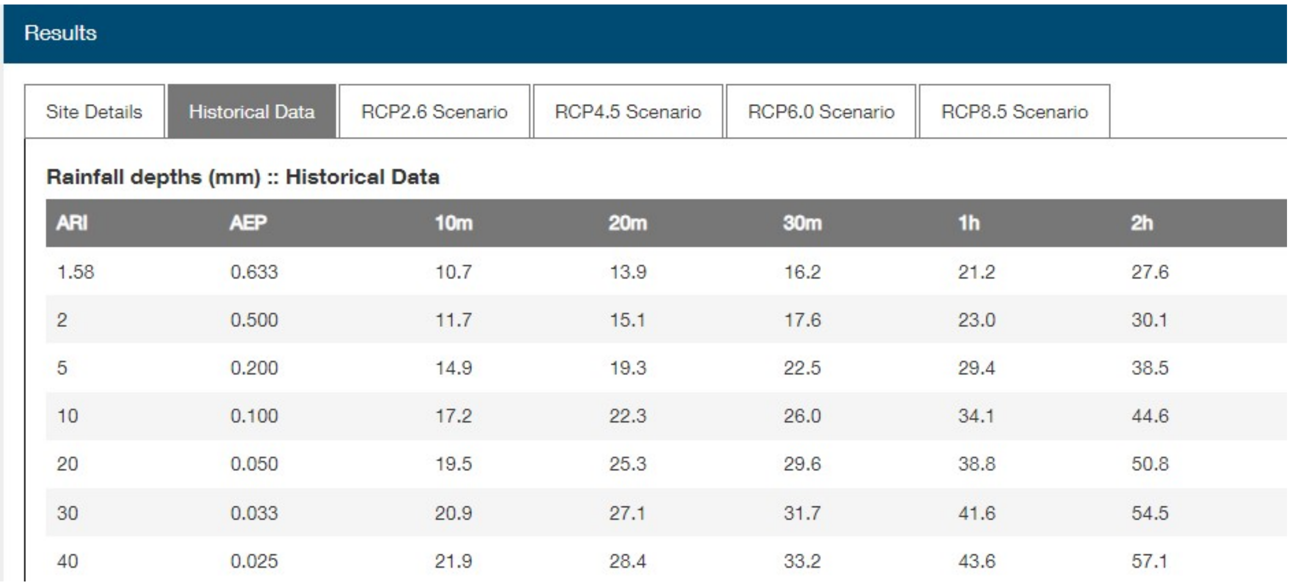
Duration	Depth	Tp108 ☑	2 years ☑	5 years ☑	10 years ☑	20 years ☑	50 years ☑	>100 years ☑
10 min	4.4 mm	0.25 years	9.6 mm	11.8 mm	13.5 mm	15.2 mm	17.4 mm	19.1 mm
20 min	8.4 mm	0.38 years	14.7 mm	18.2 mm	20.8 mm	23.4 mm	26.8 mm	29.4 mm
30 min	11.1 mm	0.44 years	18.2 mm	22.5 mm	25.7 mm	28.9 mm	33.2 mm	36.4 mm
1 hour	20.1 mm	0.85 years	25.7 mm	31.8 mm	36.3 mm	40.9 mm	47.0 mm	51.5 mm
2 hour	35.0 mm	2.05 years	34.8 mm	42.9 mm	49.1 mm	55.3 mm	63.4 mm	69.6 mm
6 hour	87.1 mm	23.46 years	53.4 mm	65.9 mm	75.4 mm	84.9 mm	97.4 mm	106.9 mm
12 hour	146.9 mm	>100 years	69.2 mm	85.5 mm	97.8 mm	110.1 mm	126.3 mm	138.6 mm
24 hour	165.2 mm	79.78 years	85.0 mm	104.9 mm	120.0 mm	135.1 mm	155.1 mm	170.2 mm

Figure 4: Depth-duration-Frequency curve for the QPE grid location at Muriwai (90767).

Table 1: Depth-duration-table for the QPE grid location at Muriwai (90767).

Duration	Depth	Tp108 ☑
10 min	4.4 mm	0.25 years
20 min	8.4 mm	0.38 years
30 min	11.1 mm	0.44 years
1 hour	20.1 mm	0.85 years
2 hour	35.0 mm	2.05 years
6 hour	87.1 mm	23.46 years
12 hour	146.9 mm	>100 years
24 hour	165.2 mm	79.78 years

Table 2: Depth-duration table from NIWA (HIRDSv4) including 250-year return period, with the 12-hour duration highlighted



Results

Rainfall depths (mm) :: Historical Data

ARI	AEP	10m	20m	30m	1h	2h
1.58	0.633	10.7	13.9	16.2	21.2	27.6
2	0.500	11.7	15.1	17.6	23.0	30.1
5	0.200	14.9	19.3	22.5	29.4	38.5
10	0.100	17.2	22.3	26.0	34.1	44.6
20	0.050	19.5	25.3	29.6	38.8	50.8
30	0.033	20.9	27.1	31.7	41.6	54.5
40	0.025	21.9	28.4	33.2	43.6	57.1

Conclusions

The above information suggests that for the 12-hour duration rainfall the ARI is >100 years, and may be in the order of 250 years. However, the calculation above the 100-year assessment becomes increasingly unreliable, primarily because of the relatively short rainfall record available in New Zealand.

For the other durations modelled, the rainfall was below the 100-year event.

2023 Rainfall and antecedent conditions

The rain experienced in the Auckland region since the 1st of January 2023 has been historically significant.

During the period from the 1st of January to the 15th of February, 491mm of rainfall has fallen at Muriwai. Compared to the average rainfall for Muriwai for January of 70mm, indicates just how much rain has fallen at this location.

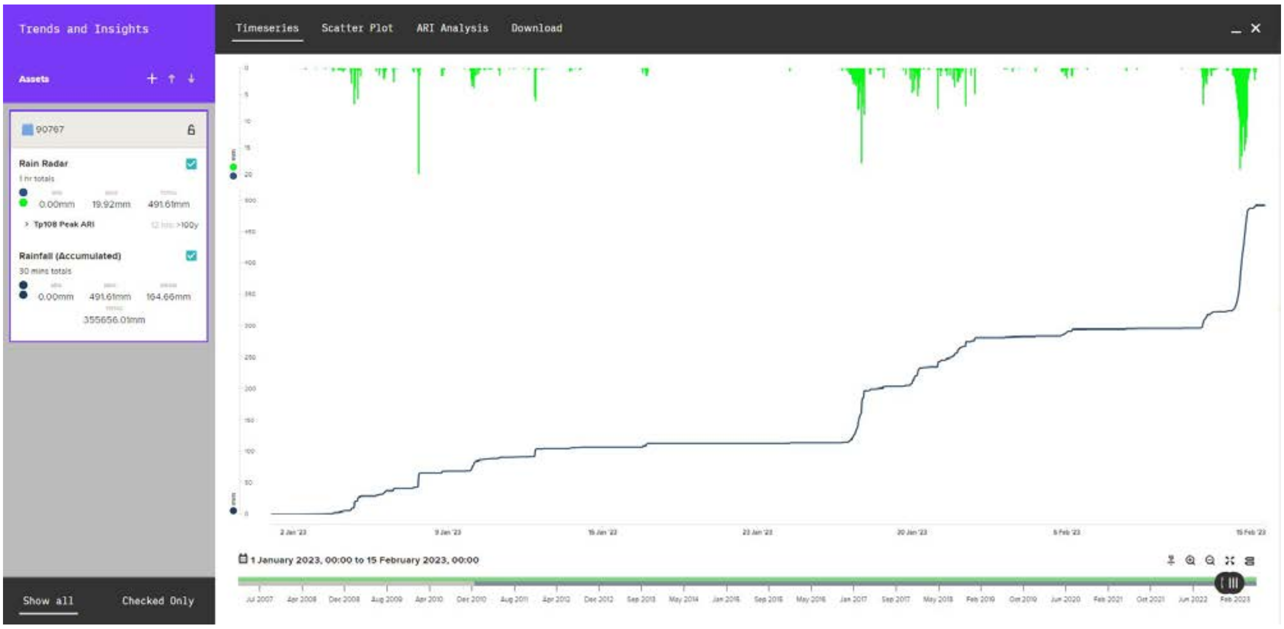


Figure 5: QPE Rain radar depths in Muriwai 1 January 2023 to 15 February 2023

Caveats

This interpretation is using data sampled from the rain gauges that doesn't include the statistics from the recent events that Auckland has experienced – the theory is that including these events in the record will shift and change the return periods and depth for all of Auckland.

Auckland Council have commissioned NIWA to undertake the analysis to re-run HIRDS 4 for Auckland to include the recent 3 years of extreme rainfall data – the results of this are expected by November 2023.

Recommendations

There are several different methods to extrapolate return periods which will all give very different and uncertain results.

It is recommended that for reporting purposes that an envelope of "risk" is determined as the ARI figures will change over time. In general for Muriwai it is considered reasonable to consider the event to be in the range of 100-250 year ARI.

For long-term risk assessment a 20% increase in rainfall intensity over the period has been projected by NIWA. A simplistic assessment (without climate modelling input) suggests this would change a 250-year ARI event to a 50-year ARI event. Risk assessment should consider both the current and future risk by re-calculating the risk taking into account this increased frequency.

For short-term risk assessments consideration should be given to the anticident ground saturation that is likely to persist at least through the winter of 2023.

ASSESSING THE ARI OF THE CYCLONE GABRIELLE EVENT – PIHA & KAREKARE

Based on the best available data from rain radar, the rain experienced during Cyclone Gabrielle in Piha was >100-year event at a 6-hour duration.

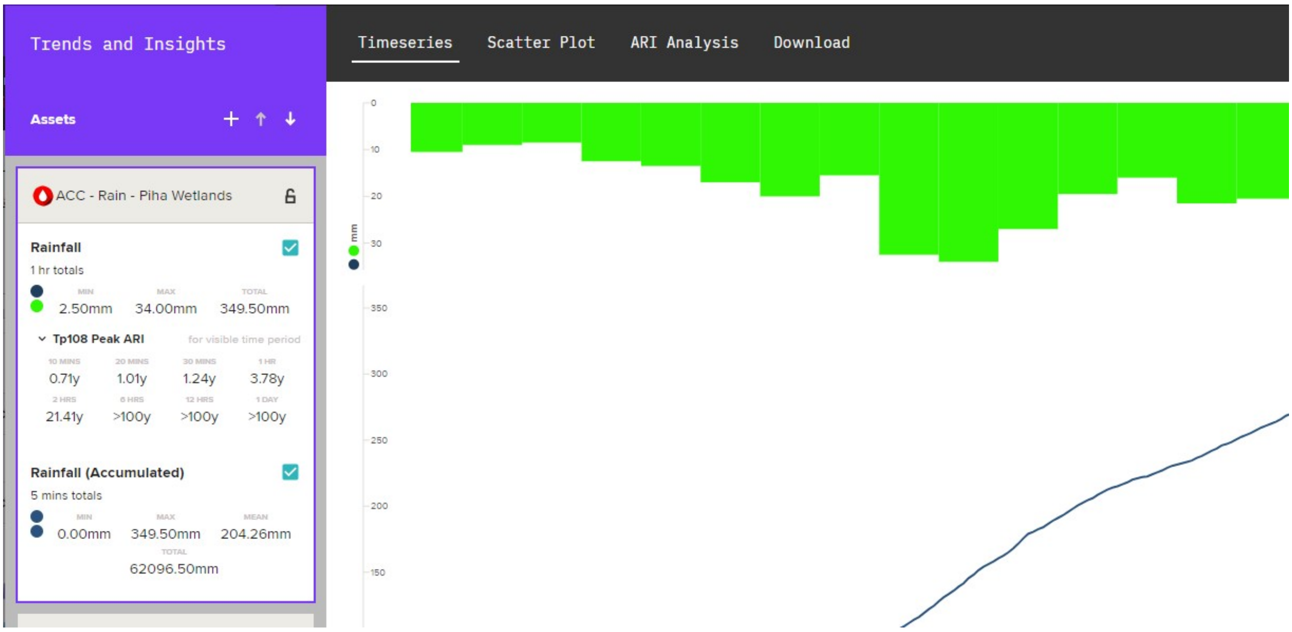
This was a significant event for the region which came off the back of a significant "wet" period, including the event on the 27th of January 2023.

In Piha there are two sources of rainfall data available for analysis.

1. Physical TB3 tipping bucket rain gauge.
2. Auckland Councils Quantitative Precipitation Estimate (QPE) Rain Radar System.

TB3 tipping bucket rain gauge.

During Cyclone Gabrielle, the tipping bucket rain gauge at Piha recorded 349.5mm of rain. This event record is presented below in **Figure 6**



ACC - Rain - Piha Wetlands

Rainfall ☑

1 hr totals

MIN	MAX	TOTAL
2.50mm	34.00mm	349.50mm

Tp108 Peak ARI for visible time period

10 MINS	20 MINS	30 MINS	1 HR
0.71y	1.01y	1.24y	3.78y
2 HRS	**6 HRS**	**12 HRS**	**1 DAY**
21.41y	>100y	>100y	>100y

Rainfall (Accumulated) ☑

5 mins totals

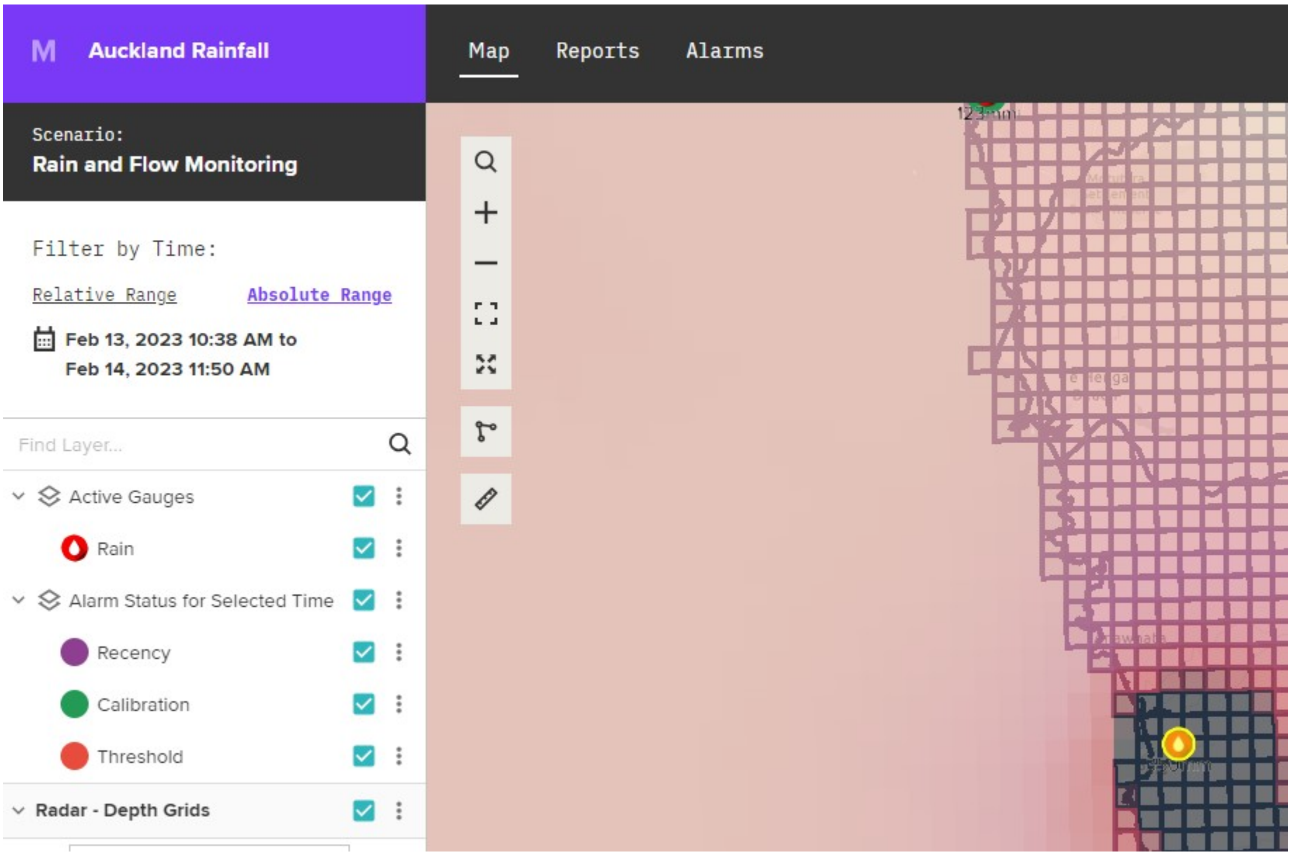
MIN	MAX	MEAN
0.00mm	349.50mm	204.26mm

TOTAL
62096.50mm

Figure 6: Piha TB3 tipping bucket rain gauge hourly totals and cumulative total

Quantitative Precipitation Estimate (QPE) Rain Radar System.

The QPE rain radar system is a real-time rainfall product which utilises the Metservice radar (reflectivity), which is transformed using a relationship to rainfall depths based on the tipping bucket gauge network. The result is spatially representative rainfall depths across the region, as shown in figure 7. This product enables full, region wide analysis of extreme rainfall events.

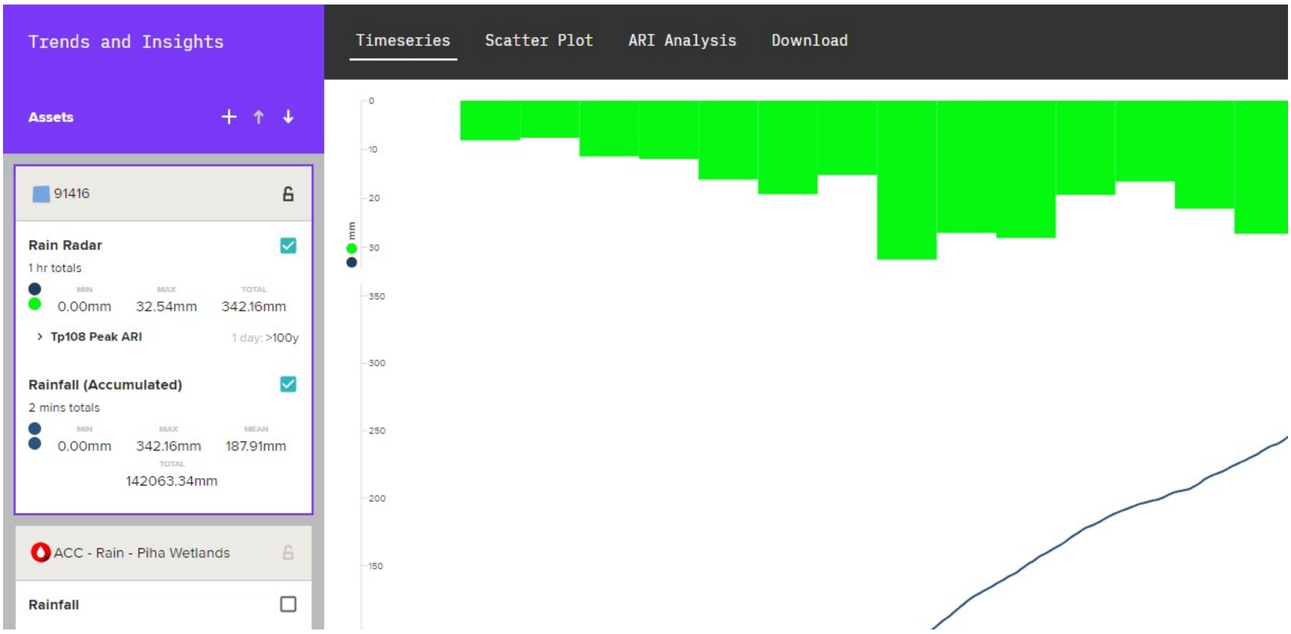


Scenario:
Rain and Flow Monitoring

Filter by Time:
Relative Range Absolute Range
Feb 13, 2023 10:38 AM to
Feb 14, 2023 11:50 AM

Active Gauges ☑
Rain ☑
Alarm Status for Selected Time ☑
Recency ☑
Calibration ☑
Threshold ☑
Radar - Depth Grids ☑

Figure 7: QPE Rain radar depth accumulations 13 February 2023 to 15 February 2023. The yellow grid location is the rainfall at the rain gauge location at Piha



91416

Rain Radar ☑
1 hr totals
MIN 0.00mm MAX 32.54mm TOTAL 342.16mm
Tp108 Peak ARI 1 day: >100y

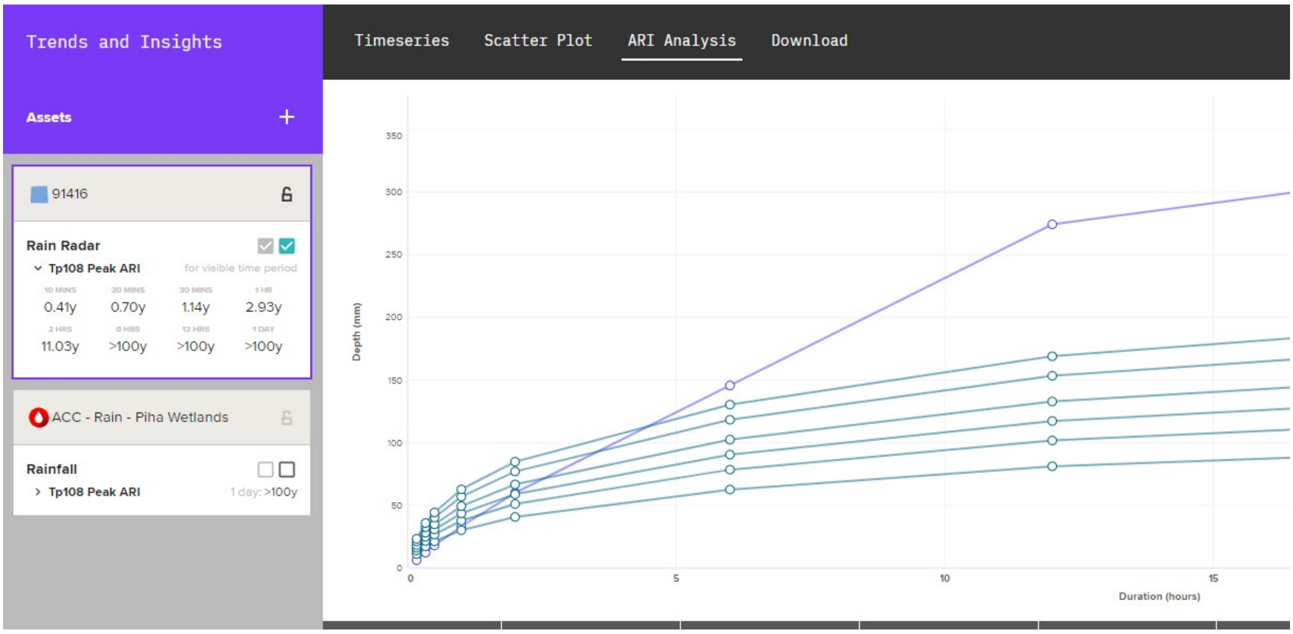
Rainfall (Accumulated) ☑
2 mins totals
MIN 0.00mm MAX 342.16mm MEAN 187.91mm
TOTAL 142063.34mm

ACC - Rain - Piha Wetlands
Rainfall ☐

Figure 8: QPE Rain radar depths in Piha 13 February 2023 to 15 February 2023

Figure 9 below shows the Depth-duration-Frequency curve for the QPE grid location at Piha. The X-axis shows duration, y axis shows depth in a given event, and the curves show the expected rainfall depths for a range of ARIs from 2 to 100-year return period (TP108, Auckland design rainfall depths).

What happened during the event is plotted in purple. This analysis and the figures in table 3 shows that the rainfall total exceeded the 100-year event from a 6 to 24 hour duration.



🟦 91416

Rain Radar ☑ ☑

Tp108 Peak ARI for visible time period

10 MINS	20 MINS	30 MINS	1 HR
0.41y	0.70y	1.14y	2.93y
2 HRS	**6 HRS**	**12 HRS**	**1 DAY**
11.03y	>100y	>100y	>100y

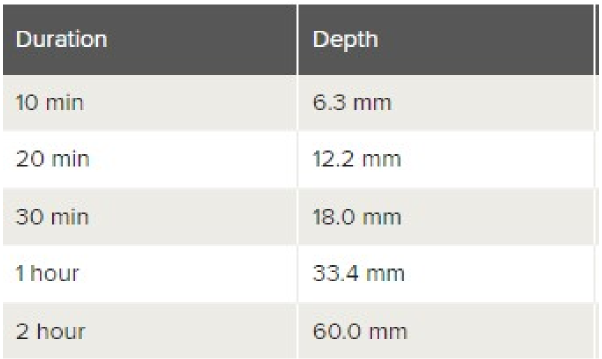
ACC - Rain - Piha Wetlands

Rainfall ☐ ☐

Tp108 Peak ARI 1 day: >100y

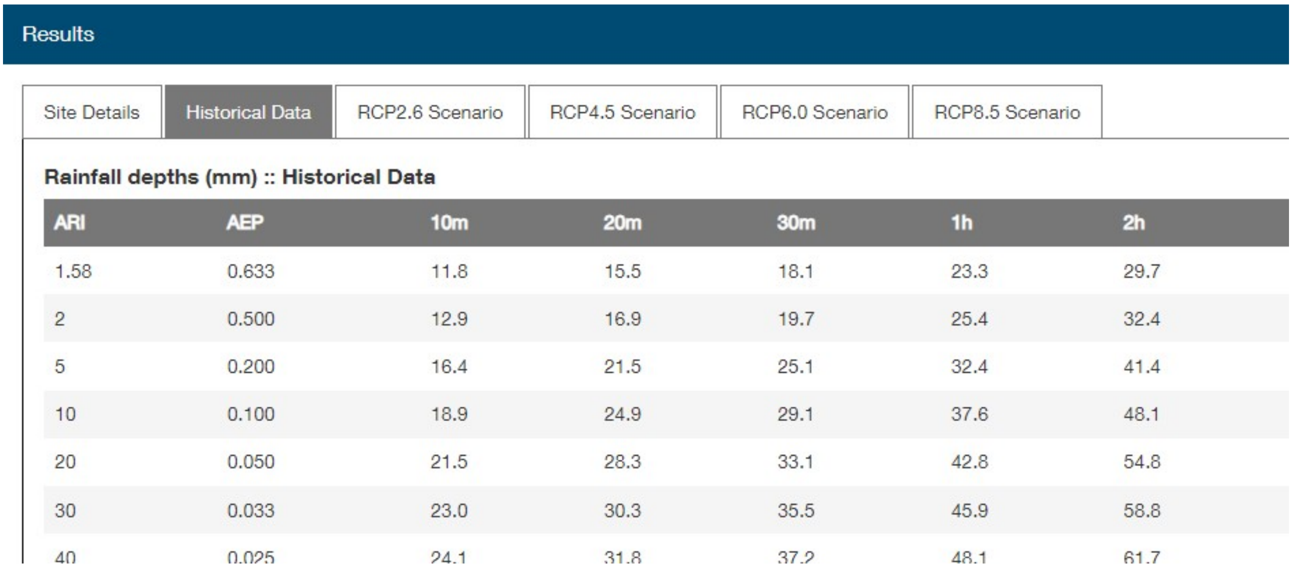
Figure 9: Depth-duration-Frequency curve for the QPE grid location at Piha (91416).

Table 3: Depth-duration-table for the QPE grid location at Piha (91416).



Duration	Depth
10 min	6.3 mm
20 min	12.2 mm
30 min	18.0 mm
1 hour	33.4 mm
2 hour	60.0 mm

Table 4: Depth-duration table from NIWA (HIRDSv4) including 250-year return period.



Rainfall depths (mm) :: Historical Data

ARI	AEP	10m	20m	30m	1h	2h
1.58	0.633	11.8	15.5	18.1	23.3	29.7
2	0.500	12.9	16.9	19.7	25.4	32.4
5	0.200	16.4	21.5	25.1	32.4	41.4
10	0.100	18.9	24.9	29.1	37.6	48.1
20	0.050	21.5	28.3	33.1	42.8	54.8
30	0.033	23.0	30.3	35.5	45.9	58.8
40	0.025	24.1	31.8	37.2	48.1	61.7

Conclusions

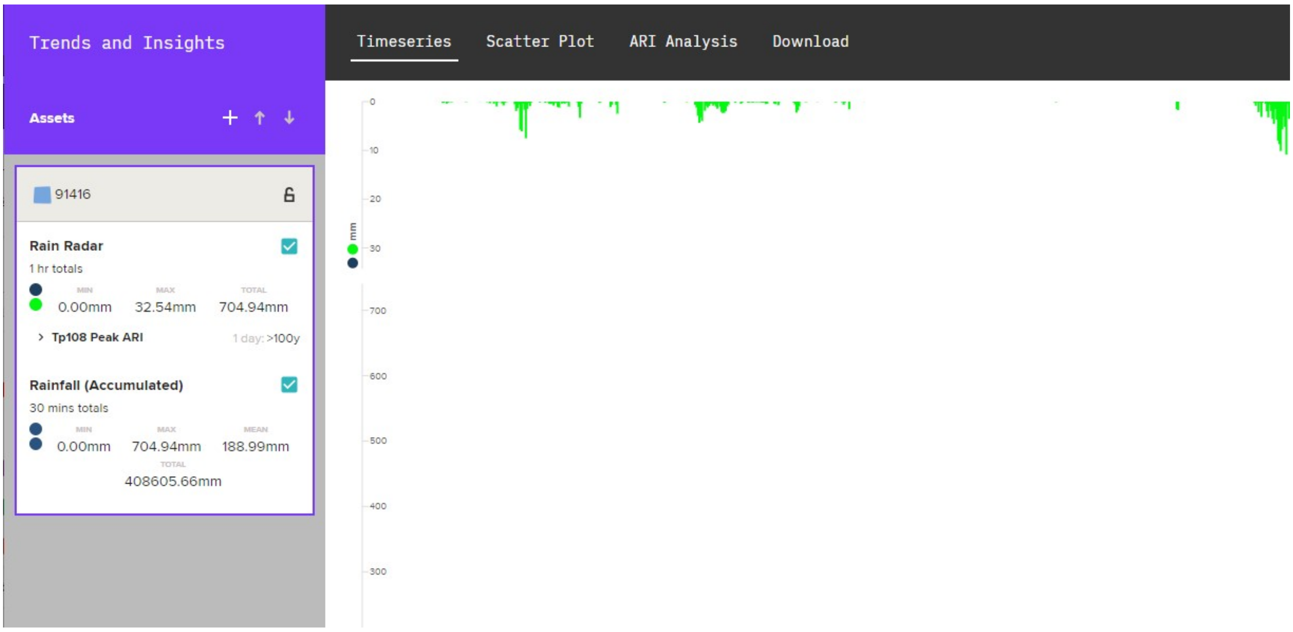
The above data suggests that for the 6 to 24-hour duration the ARI is >100 years and may be in the order of 250 years. However, the calculation above the 100-year assessment becomes increasingly unreliable, primarily as a result of the relatively short statistical rainfall records available in New Zealand.

For the other durations modelled, the rainfall was below the 100-year event.

2023 Rainfall and antecedent conditions

The rain experienced in the Auckland region since the 1st of January 2023 has been historically significant.

During the period from the 1st of January to the 15th of February, 704 mm of rainfall has fallen at Piha. Compared to the average rainfall for Piha for January of 70mm, indicates just how much rain has fallen at this location.



91416

Rain Radar ☑
1 hr totals
MIN 0.00mm
MAX 32.54mm
TOTAL 704.94mm
Tp108 Peak ARI 1 day: >100y

Rainfall (Accumulated) ☑
30 mins totals
MIN 0.00mm
MAX 704.94mm
MEAN 188.99mm
TOTAL 408605.66mm

Figure 10: QPE Rain radar depths in Piha 1 January 2023 to 15 February 2023

Caveats

This interpretation is using data sampled from the rain gauges that doesn't include the statistics from the recent events that Auckland has experienced – the theory is that including these events in the record will shift and change the return periods and depth for all of Auckland.

Auckland Council have commissioned NIWA to undertake the analysis to re-run HIRDS 4 for Auckland to include the recent 3 years of extreme rainfall data – the results of this are expected by November 2023.

Recommendations

There are several different methods to extrapolate return periods which will all give very different and uncertain results.

It is recommended that for reporting purposes that an envelope of "risk" is determined as the ARI figures will change over time and as these events are incorporated into the statistical record. In general, for Piha it is considered reasonable to consider the event to be in the range of 100-250 year ARI.

For long-term risk assessment a 20% increase in rainfall intensity over the period has been projected by NIWA. A simplistic assessment (without climate modelling input) suggests this would change a 250-year ARI event to a 50-year ARI event. Risk assessment should consider both the current and future risk by re-calculating the risk considering this increased frequency.
For short-term risk assessments consideration should be given to the antecedent ground saturation that is likely to persist at least through the winter of 2023.

ASSESSING THE ARI OF THE AUCKLAND ANNIVERSARY FLOODS – CENTRAL AUCKLAND

Auckland experienced its largest ever rain event on the 27th January 2023. The majority of urban Auckland received rainfall in excess of the 100 year event. Thousands of houses and commercial buildings were inundated with floodwater.

Extreme rainfall was widespread across the region, with a wide front tracking in a southerly direction from the Northeast, impacting the Hibiscus Coast, North Shore, West, and Central Auckland before passing to the South of the Auckland Region.

While the rain was widespread across the region, including reported flooding in the Northern and Southern Rural areas, it was our urban city catchments which bore the brunt of the event and have experienced significant flooding issues.

Regionally there are two sources of rainfall data available for analysis.

1. Physical TB3 tipping bucket rain gauge.
2. Auckland Councils Quantitative Precipitation Estimate (QPE) Rain Radar System.

TB3 tipping bucket rain gauge.

Rainfall totals during the period from 00:00am Friday 27/01/2023 to 07:00am Saturday 28/01/2023 were in excess of 230mm at many locations across the region's urban extents, with the maximum recorded total during this period being 318mm. Most of the rain fell in a 4 hour period. The Onehunga @ Harbourside rain gauge measured 146 mm of rainfall in a 2-hour period, the average total rainfall for January is 73.8mm.

Table 5: Summary rainfall statistics by stormwater operational area 12am 27 Jan to 7am 28 Jan

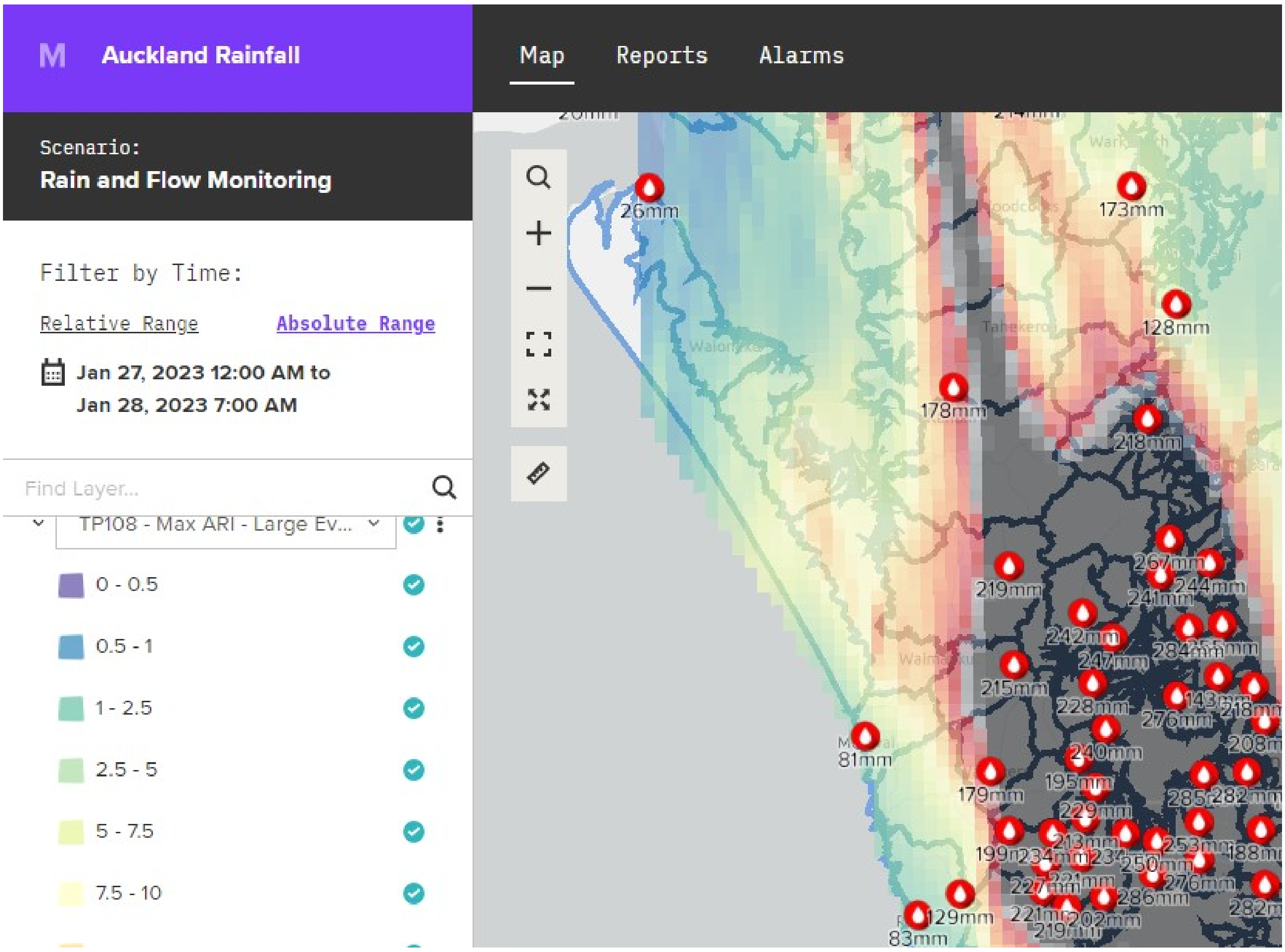
	Total (00:00 27 Jan 07:00 28 Jan) mm		**1 Hour Total mm**	
	Max	Average	Max	Average
North	284	193	75	46
Central/West	286	217	91	50
South	263	163	75	32

Summary figures are calculated from all rain gauges in each of the 3 sub-regional areas. i.e., the max is the rain gauge in each area with the highest total for the event. The average is the average rain across all the rain gauges in that sub region. For example, in North there are 25 rain gauges which were averaged to get 193mm

Quantitative Precipitation Estimate (QPE) Rain Radar System.

The QPE rain radar system is a real-time rainfall product which utilises the Metservice radar (reflectivity), which is transformed using a relationship to rainfall depths based on the tipping bucket gauge network. The result is spatially representative rainfall depths across the region, as shown in **Figure 11**.

This product enables full, region wide analysis of extreme rainfall events.



Auckland Rainfall

Scenario:
Rain and Flow Monitoring

Filter by Time:
Jan 27, 2023 12:00 AM to
Jan 28, 2023 7:00 AM

TP108 - Max ARI - Large Ev...

🟪 0 - 0.5 ✓
🟦 0.5 - 1 ✓
🟩 1 - 2.5 ✓
🟩 2.5 - 5 ✓
🟨 5 - 7.5 ✓
🟨 7.5 - 10 ✓

Figure 11: Recorded Rainfall Radar Max Average Recurrence Interval (ARI). The black area is where rainfall was greater than a 100yr ARI (for any of the 10,20,30 min and 1,2,6,12,24-hour durations) In the black area the event was greater than 100yr for the vast majority of durations.

Conclusions

The above data suggests that for the majority of the region the ARI for this event is >100 years and may be in the order of 250 years. However, the calculation above the 100-year assessment becomes increasingly unreliable, primarily because of the relatively short statistical rainfall records available in New Zealand.

Further analysis of this event by NIWA (https://niwa.co.nz/news/auckland-suffers-wettest-month-in-history) highlights the extreme nature of this event, indicating that this event could be described a “at least a 1-in-200-year event”.

Caveats

This interpretation is using data and models sampled from rain gauges that doesn't include the statistics from the recent events that Auckland has experienced, the theory is that including these events in the record will shift and change the return periods and depth for all of Auckland.
Auckland Council have commissioned NIWA to undertake the analysis to re-run HIRDS 4 for Auckland to include the recent 3 years of extreme rainfall data – the results of this are expected by November 2023.

Recommendations

There are several different methods to extrapolate return periods which will all give very different and uncertain results.

It is recommended that for reporting purposes that an envelope of "risk" is determined as the ARI figures will change over time and as these events are incorporated into the statistical record. In general, for the Auckland Anniversary floods it is considered reasonable to consider the event to be in the range of 100-250 year ARI.

For long-term risk assessment a 20% increase in rainfall intensity over the period has been projected by NIWA. A simplistic assessment (without climate modelling input) suggests this would change a 250-year ARI event to a 50-year ARI event. Risk assessment should consider both the current and future risk by re-calculating the risk considering this increased frequency.
For short-term risk assessments consideration should be given to the antecedent ground saturation that is likely to persist at least through the winter of 2023.

For further information or clarification of the figures presented please contact the undersigned.

Kris Fordham | Mātanga Aporei - Principal Hydrometric Analytics
Te Tari o Ngā Waiora - Healthy Waters | Infrastructure and Environmental Services
Mobile 021625340
Auckland Council, Level 17, Auckland House, 135 Albert Street, Auckland 1010
Visit our Website: **www.aucklandcouncil.govt.nz**

Appendix E-2

85 Domain Crescent Landslide Risk Assessment

Waitākere Coastal Communities Landslide Risk Assessment

85 Domain Crescent, Muriwai

Auckland Council

30 April 2024

→ **The Power of Commitment**

Project name	AC Geo Panel - Waitākere Coastal Communities LHRA
Document title	Waitākere Coastal Communities Landslide Risk Assessment | 85 Domain Crescent, Muriwai
Project number	12612462
File name	12612462- RiskAssess85 Domain MuriwaiFINAL.docx

Status Code	**Revision**	**Author**	**Reviewer**		**Approved for issue**		
			Name	**Signature**	**Name**	**Signature**	**Date**
S4	0	Ryan Hayes	Don Macfarlane	DMacfarlane	Matt Howard	MHoward	30/04/2024
[Status code]							
[Status code]							
[Status code]							

GHD Limited
Contact: Matt Howard, Technical Director - Engineering Geology | GHD
27 Napier Street, GHD Centre Level 3
Freemans Bay, Auckland 1010, New Zealand
T +64 9 370 8000 | **F** +64 9 370 8001 | **E** aklmail@ghd.com | **ghd.com**

→ **The Power of Commitment**

Contents

Table index

Figure index

Appendices

1. Introduction

1.1 Background

Two significant rainfall events affected the Waitakere area in late January and early February, resulting from the impacts of ex-tropical cyclones Hale and Gabrielle, respectively.

The Cyclone Gabrielle weather event of 14 February 2023 resulted in widespread catastrophic flooding and slope instability in the settlement of Muriwai where several debris avalanches (which included rocks and trees) occurred, some of which turned into saturated debris flows as they travelled downslope. These flows resulted in damage to buildings and infrastructure. Two fatalities occurred due to impact of landslides on private dwellings. This tragic event was similar to a 1965 storm event that also claimed two lives.

Following the February event, rapid building assessment of residential properties was undertaken in Muriwai, with some houses having access by owners restricted (a yellow placard – e.g. access in daylight hours only) and some for which no access was permitted (a red placard).

GHD has been engaged by Auckland Council (AC)[1] to carry out landslide risk assessments and to provide associated landslide risk management advice and geotechnical investigations recommendations in the Waitakere area, specifically for the residential areas of Muriwai, Piha and Karekare. These assessments were necessary due to widespread, damaging landslides associated with Cyclone Gabrielle in February 2023. GHD has completed a landslide risk assessment[2], whereby some properties were identified as having an unacceptably high risk of being impacted by future large landslides.

1.2 Purpose of this report

The residential property at 85 Domain Crescent, Muriwai ('the site') has been assessed by GHD as having an acceptable risk from large scale landslides[3] (see the November 2023 report). However, a localised, damaging landslide has occurred, and the purpose of this assessment is to carry out a Quantitative Landslide Risk Assessment (QRA) to estimate the risk of Loss of Life to individuals at the property. The outcome of the QRA will be used to inform subsequent property risk categorisation and building placard designation review by AC.

1.3 Scope

The scope of work requested by AC is as follows:

- Review available historical and recent imagery including LiDAR.
- Review pertinent historical data and GHD work undertaken as part of the wider Muriwai landslide risk assessment reported in GHD (November 2023).
- Undertake a site engineering geological assessment of landslide hazards at the impacted property.
- Undertake a QRA where landslide hazards have been identified that pose a Loss of Life landslide risk using the Australian Geomechanics Society Practice Note Guidelines for Landslide Risk Management, commonly known as AGS (2007c).
- Deliver report(s) documenting the QRA inputs and outcome.

Specifically excluded are an assessment of property risk, site specific subsurface geotechnical investigations, service inspections, and groundwater monitoring.

This assessment considers geotechnical matters only. There may be other non-geotechnical considerations that affect the final property risk categorisation or placard designation of which GHD are not aware, such as flood risk and structural damage to property.

---

[1] Under Contract CW198379, Master Services Agreement CCCS: CW74240 dated 7/09/2019

[2] Dated 03/11/2023, document file ref 12612462_Overall Report FINALRev0.docx

[3] In the GHD November 2023 report, 'large scale' landslide hazards refers to landslides originating from the main escarpment that typically have a volume of more than about 50 m3 with the potential to cause total or partial collapse of a dwelling.

Identification of options for the mitigation of geotechnical hazards has not been undertaken as part of this study.

Although considered unlikely, GHD reserves the right to amend the opinions, conclusions and recommendations provided within this report, should additional geotechnical information become available.

1.4 Our Approach

GHD have completed a landslide risk assessment for Muriwai which assessed the risk to life of large-scale landslide hazards to inform possible future dwelling hazard designations. The assessment was limited to ‘large scale’ landslide hazards originating from the main escarpment located to the south-east of Muriwai because the initial placard assessment was largely aimed at mitigating risks associated with these.

Smaller, more localised landslide hazards that could originate (or may have already initiated) from other areas in Muriwai such as within the footprint of individual residential properties were not considered in the risk assessment. However, these have the potential to cause damage to dwellings and subsequently pose a risk to life for residents, partly due to the relatively steep topography and the potential for high travel velocity.

The approach of identifying landslide hazards over large and common source areas, such as that used for the November 2023 Muriwai assessment, does not capture numerous, smaller scale landslides. For this reason, a QRA is presented for the individual property (85 Domain Crescent) based on an assessment of the site that includes site observations and a desktop review of available information. The results aid with informing the QRA with regards to the presence of existing and historical landslide hazards and site-specific slope conditions.

The QRA undertaken for this report assesses risk to life to occupants of the dwelling. The assessment considers a number of hazard scenarios as follows:

1. the **most likely significant landslide hazard** based on the observed hazards with respect to the mapped landslides and their distribution within the broader landscape. In addition, considerations of the hazard relationship to topography, position on the hillslope and proximity to the elements at risk are also included. This represents a credible hazard scenario following a triggering event with a similar frequency as the February 2023 event.
2. Existing geohazards that have resulted from recent failures with the potential to pose risk to life, such as regression and/or remobilisation of translational failures that are upslope or downslope of a dwelling or failure of oversteepened fill and cut slopes. These represent hazards that exist at the site and may be initiated by a more frequent triggering event.
3. Other possible geotechnical slope instability hazards that have potential to pose a risk to life such as failures of fills, cuttings and failed retaining walls. These also represent hazards that may be triggered by a more frequent event.

The process of risk assessment involves estimation of likelihood, consequence and risks based on available information for the study site. The methodology used for the QRA is outlined in Appendix A. The site-specific input parameters and uncertainties are described in Section 3.

A glossary of terminology is presented in Appendix B.

2. Site conditions

2.1 Site description

The site is located at 85 Domain Crescent, Muriwai, legally described as Lot 64 DP 39644 and it has an approximate area of 845 m^2. A GHD engineering geologist inspected the site on 11 December 2023. No inspection was undertaken within or under the house, however, an insurance assessment report that was made available to us by AC provides photos of the interior[4].

As shown in Figure 2.1, the affected property is located on the lower portion of the approximately 80 m high main escarpment that is aligned to the northeast and separates the township between lower-lying plateaus to the west (near sea level), and higher areas to the south and east. Locally, the main escarpment extends from Domain Crescent at its base at an elevation of approximately 60 m RL, to Oaia Road at its crest at an elevation of approximately 150 m RL. The slopes encompassing the site have an average slope angle of approximately 32°.

The dwelling is a three-storey structure that sits on timber poles and it is located near the base of the slope, adjacent to Domain Crescent. The building platform may have been modified to accommodate the structure, and the dwelling is accessed via a concrete driveway. A steep (generally 30-40°) natural, vegetated slope behind the dwelling extends to an elevation of approximately 100 m above sea level, where it meets a prominent north-trending ridgeline at the eastern extent of the property boundary.

Two ‘large’ landslides (mapped on Figure 2.1) originating to the west of the site occurred during Cyclone Gabrielle but did not affect the dwelling. A third, smaller scale, localised failure originating from within the property boundary at approx. 83 m RL developed into a debris flow which impacted the rear of the dwelling causing structural damage.

One of the large-scale failures originating on slopes at higher elevations above the site (approx. 120 m RL) developed into a channelised debris flow reaching Domain Crescent. Silt discharge from the debris partially inundated the elevated timber deck on southern side of the dwelling.

---

[4] Tonkin + Taylor, 19 June 2023. Claim for Natural Disaster (Landslip) Damage Sarah Gerritsen, 85 Domain Crescent, Muriwai, Auckland, 0881 EQC/Insurer Claim Number C90154866

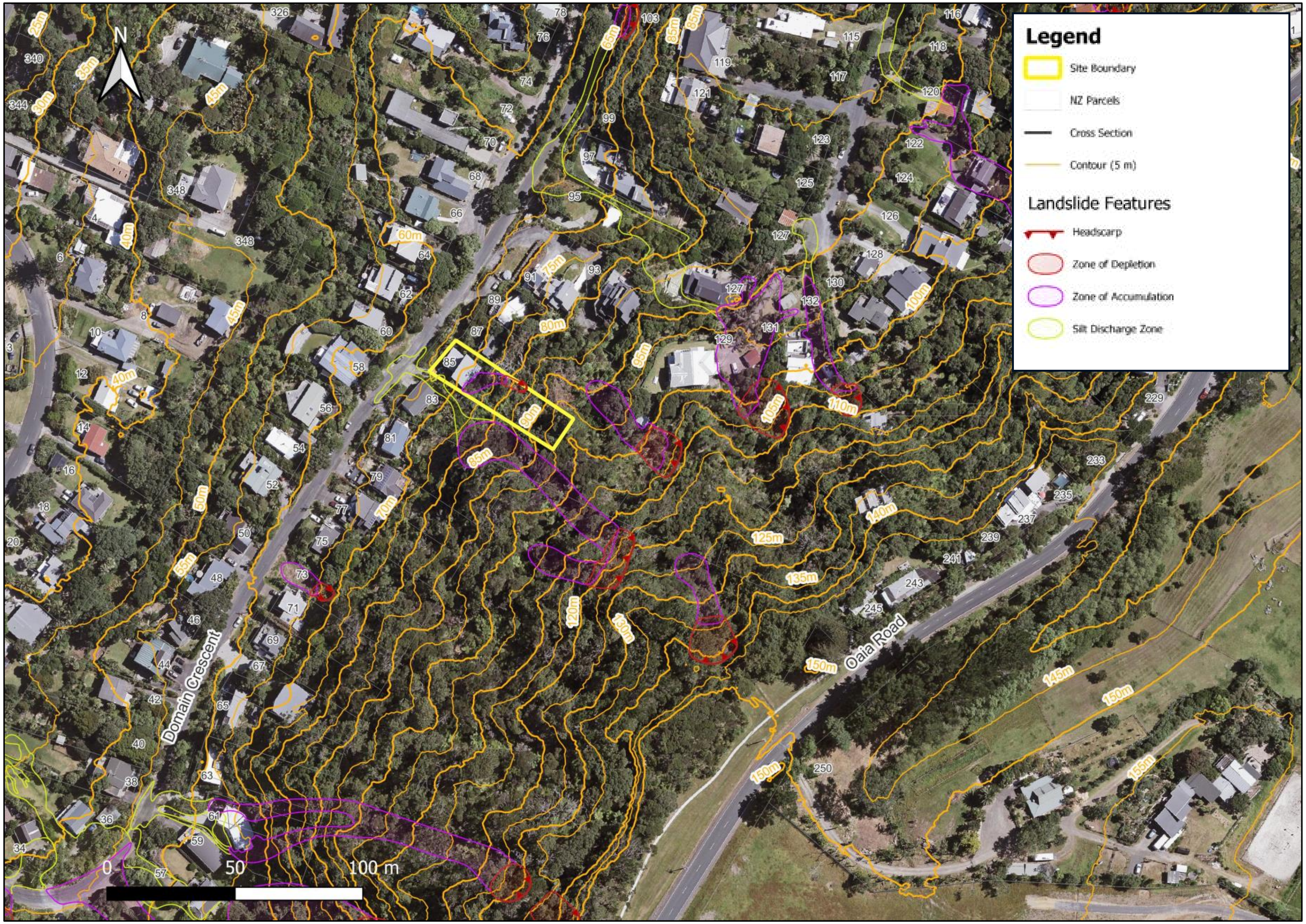


Figure 2.1 *Site location along Domain Crescent*

2.2 Site services and sources of water

Auckland Council’s GeoMaps presents relevant underground services and hydrologic information for the site. An excerpt of the data is presented in Figure 2.2.

Two overland flow paths are mapped to the north and south of the property boundary originating at approximately 105 m RL and 75 m RL, respectively, connecting approximately 50 m downslope, west of the dwelling. Both overland flow paths have a catchment size of approximately 2000 m^2 – 4000 m^2.

The travel paths of the debris associated with the two large scale landslides above the site, to the north and south, appear to correlate with the mapped overland flow paths.

No underground services associated with water are mapped on the slopes above the dwelling.

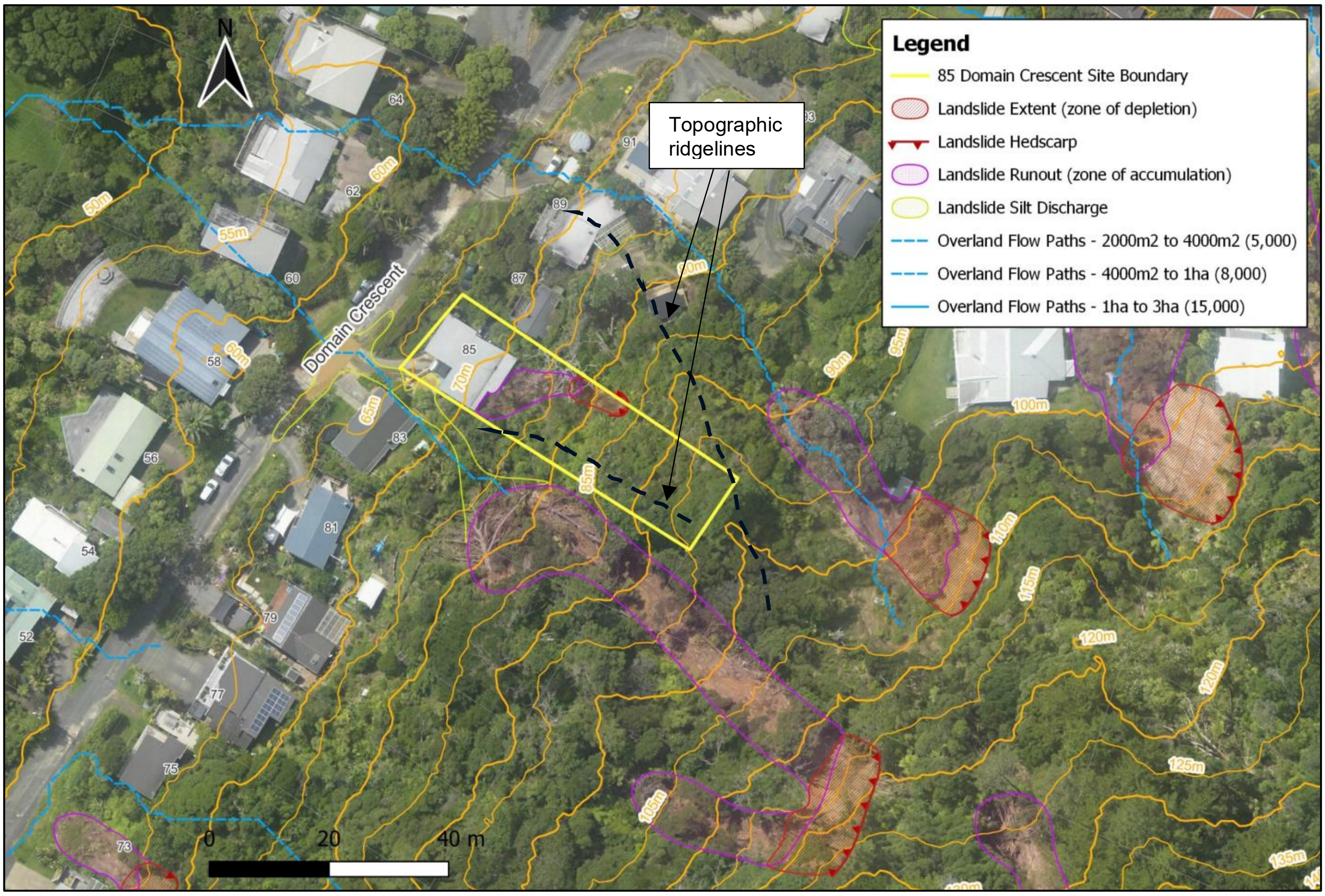


Figure 2.2 Overland flow paths and underground services for the site (source: Auckland Council GeoMaps).

2.3 Published geology

The published 1:50,000 scale geological map of the area (Hayward, 1983) indicates the site is entirely underlain by the Awhitu Sand Formation (mp), part of the Kaihu Group (Figure 2.3).

Awhitu Sands (‘qs’) are Pliocene aged (less than 2 Mya) characterised as ‘coarse sand, clayey, often limonitised (as laterally discontinuous layers), with minor tuff, lignite and siltstone’ (Hayward, 1983). The formation originated as coastal sand deposits. Awhitu Sands are generally oxidised to an orange-brown colour when exposed at the surface, resulting in a weak iron-cementation that allows for the development of large, more than 50 m high steep slopes, such as the escarpment.

The formation is weakly bedded and cross-bedded at the sub metre scale. Locally the formation is inferred to dip north and eastward at a shallow angle. Occurrences of silty/clayey horizons are occasionally visible in outcrop and have been encountered within boreholes, however it is unclear how persistent they are spatially.

Although not mapped, more recent colluvium material formed as a result of ongoing erosion and periodic landsliding associated with escarpment recession is likely present on the basal/lower slopes of the escarpment.

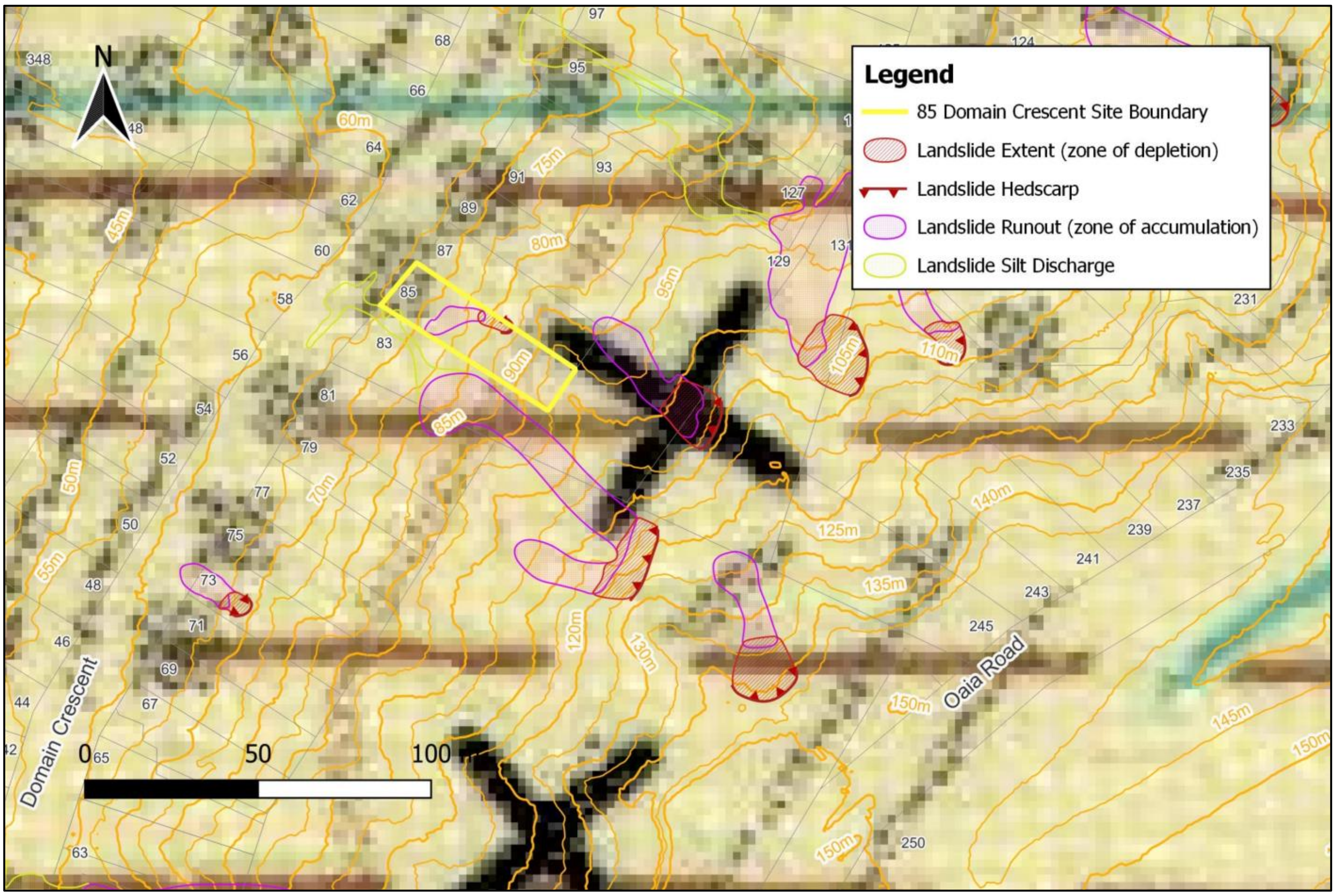


Figure 2.3 *Excerpt of the Waitākere 1:50,000 scale geological map (Hayward, 1983[5]), illustrating the underlying geology at the site location.*

---

[5] Hayward, B.W. 1983: Sheet Q11, Waitakere. Geological Map of New Zealand 1:50,000 Map

2.4 Historical data summary

A summary of the historical data relevant to 85 Domain Crescent is presented in Table 2.1.

Table 2.1 Summary of historical data

	Applicable data available	Notes
Historic aerial photos	- 1940 - 1950 - 1953 - 1975 - 2000 - 2004 - 2008 - 2010-2011 - 2015-2017 - 2022	- No obvious evidence of instability was identified from the historical aerials within the property itself. - Evidence of wider scale erosion evident from 1940, where many of the spurs leading off main escarpment are bare as well as section of the crest of the escarpment. Suggests ongoing erosion of surficial soil. No regression of escarpment observed. - Photos sourced from Retrolens and Auckland Council Geomaps.
NZ Geotechnical database	One borehole (BH-MH05) completed by GHD in August 2023. Located 15 m west of south-west corner of property boundary (see Figure 2.6).	- 10.95 m deep borehole. - 0 – 5.6 m: Ancient colluvial deposits generally comprising sandy silt and silty sand. - 5.6 – 10.95 m: Awhitu sand formation comprising variably cemented sand (medium dense to very dense)
Council GeoMaps	Overland flow data from Auckland City Council ArcGIS.	- Discussed in Section 2.2.
Rapid building Assessment Geotech reporting	N/A	N/A
Independent geotechnical reports	Soil & Rock Consultants (2001) report for proposed house extension. Babbage Consultants geotechnical appraisal advice (2000) Tonkin & Taylor (2023) EQC report	- Summarised in Table 2.2 below.
Anecdotal information	N/A	N/A
LiDAR Imagery	Feb 2023 Digital Terrain Model.	- Headscarps in the escarpment crest suggest ongoing recession through debris flows. - Headscarps also seen on smaller ridgelines extending down the escarpment. - Possible hummocky ground on the natural slopes above the dwelling on 85 Domain Crescent.

Table 2.2 Historical geotechnical reports summary

Geotechnical report	Relevant comments
Soil & Rock consultants – Geotechnical investigation for proposed extension to existing dwelling (Jan 2001)	- Evidence of shallow surface creep over the property with the formation of terracettes and the presence of hummocky ground on steeper slopes and shallow rooting trees frequently exhibiting downslope leaning. - No evidence of obvious large scale instability just shallow surface creep. - Local topography indicates that surface runoff from above the dwelling is concentrated into an overland flow path feature that runs through the southern corner of the property and continues through into the adjacent property to the southwest. - Four hand augers were completed to depths of 2.3 to 3.4 m encountered loose to medium dense sand silts and silty sands overlying dense to very dense (cemented) silts/sands. Subsurface interpretation of the site illustrated on Figure 2.4 below. - An inground barrier pile wall was recommended to support the proposed cut bench.
Babbage Consultants – Geotechnical appraisal and advice re: slip affecting 60 Domain Crescent (June 2000)	- Slopes below the road (Domain Crescent) failed, developing into a debris flow, leaving a 5-6 m high scarp. - Stormwater pipes observed protruding from scarp. - The cause of the slip likely water entry into the slope through the pipes. Progressive landslide movement may have restricted stormwater discharge. - No signs of movement observed affecting No. 85. The slopes above the house however clearly exhibiting evidence of periodic localised movement.
Tonkin & Taylor – Claim for Natural Disaster (Landslip) Damage (EQC report)	- Details property damage including damage to dwelling (racking and twisting entire building), inundation of deck and damage to services. - Determined that there is an imminent risk of regression of the landslip headscarp. - Recommended conceptual remedial works include; BioCoir matting over failed surface, hydroseeding, construction of a timber pole catch fence following removal of debris.

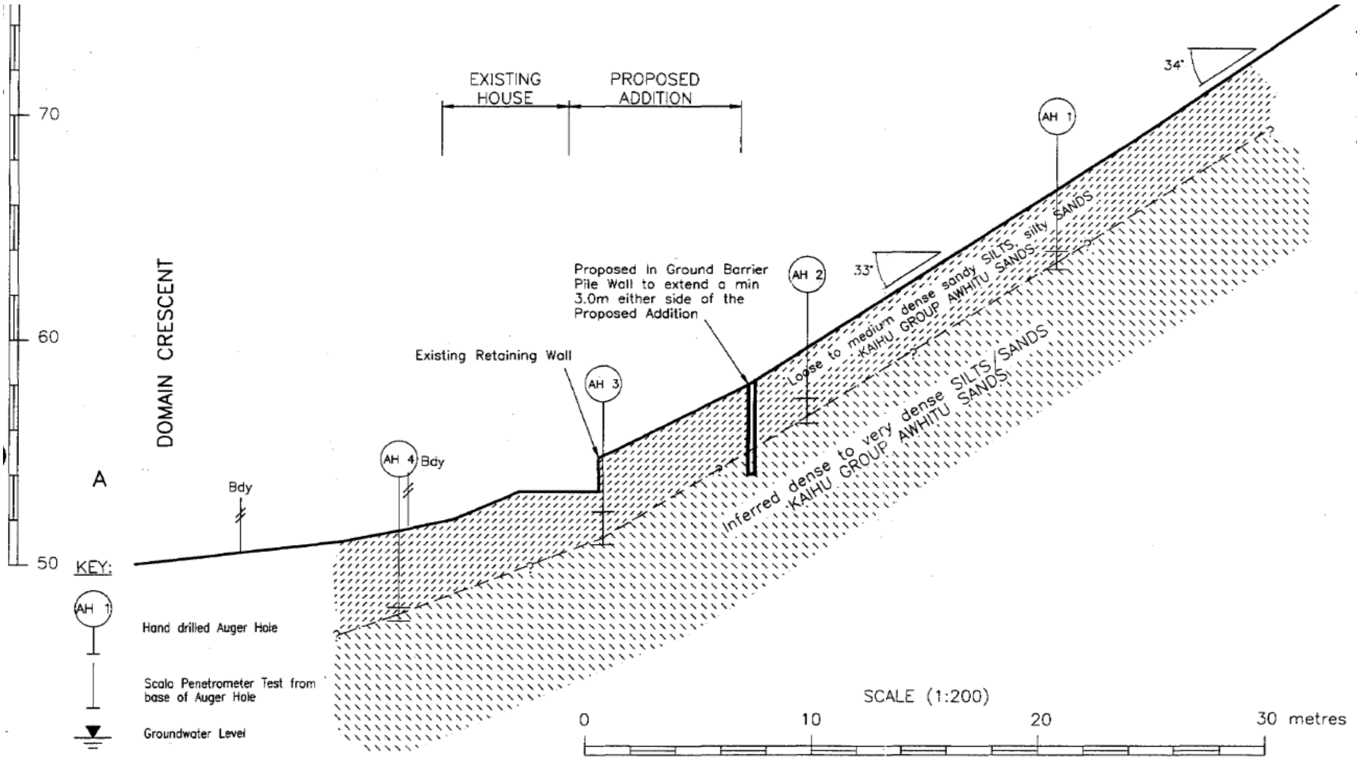


Figure 2.4 Interpreted geological cross section (Excerpt from Soil & Rock Consultants, 2001 (note: this report was issued for the proposed building which has since been constructed)

2.5 Engineering geological model

2.5.1 Awhitu Sand Formation

Awhitu Sands are exposed within the entire escarpment and have generally been described as medium dense to very dense sands overlying massive, extremely weak, moderately weathered, iron-cemented fine to coarse sandstone. Irregular layers of clay and silt rich material are typically spaced every 5-10 m and relatively thin (less than 1.0 m and often less than 0.1 m). The strength profile of the Awhitu Sands displays a relatively linear increase with depth.

The in-situ nature of the Awhitu Sands suggests they are relatively permeable. However, as discussed in the November report there is also significant evidence for perched groundwater tables shown by:

- Multiple occurrences of groundwater seeps or springs emerging within the middle and base of the escarpment slope face, from above underlying (presumed aquiclude) layers of clay and silt rich beds as well as heavily oxidised iron pans
- Variable and sharply changing weathering profile with localised layers of cemented iron oxidised sand between un-oxidised material at depth.

2.5.2 General landslide characteristics

As described in the November report (GHD 2023), the landslides identified across Muriwai following the February 2023 event can be categorised into two types based on their physical characteristics as follows:

Large slips: typical headscarp widths of 30-70 m, with source and debris runout areas more than 100 m in length, often extending well past the base of the escarpment onto the flatter slopes below, and

Smaller isolated slips: generally with headscarp widths of less than 30 m and extending less than 50 m. As a result debris from these landslides generally did not reach the base of the escarpment.

2.5.3 Landslide impacting the site

The landslide that occurred within the site is illustrated by site mapping on Figure 2.5 and is also shown in the context of different imagery on Figure 2.6 and Figure 2.7 below. An interpretive cross section prepared through the site is presented in Figure 2.12. Ground conditions have been interpreted from a combination of historical data, site mapping and nearby geotechnical investigation data. The cross section is indicative only and may not be representative of actual conditions.

The landslide headscarp (Figure 2.8) has an approximate width of 7 m and is approximately 10 m above the rear of the dwelling near the crest of a ridgeline. Following a high degree of ground saturation, it initiated on a 30-35° vegetated slope as a shallow (~ 0.5 m deep) translational failure (Figure 2.9) which developed into a debris flow, likely entraining additional material on its descent. The initial landslide source volume was approximately 20 m^3, increasing to approximately 60-80 m^3 following entrainment. The landslide impacted the rear of the dwelling (Figure 2.10). The resulting damage to the dwelling included widespread structural deformation (see Figure 2.11 and T+T, 2023) with no immediate building collapse. Inundation of the of the decking was also recorded, which, according to our mapping is likely a result of secondary silt discharge from the large-scale landslide that occurred to the south of the site.

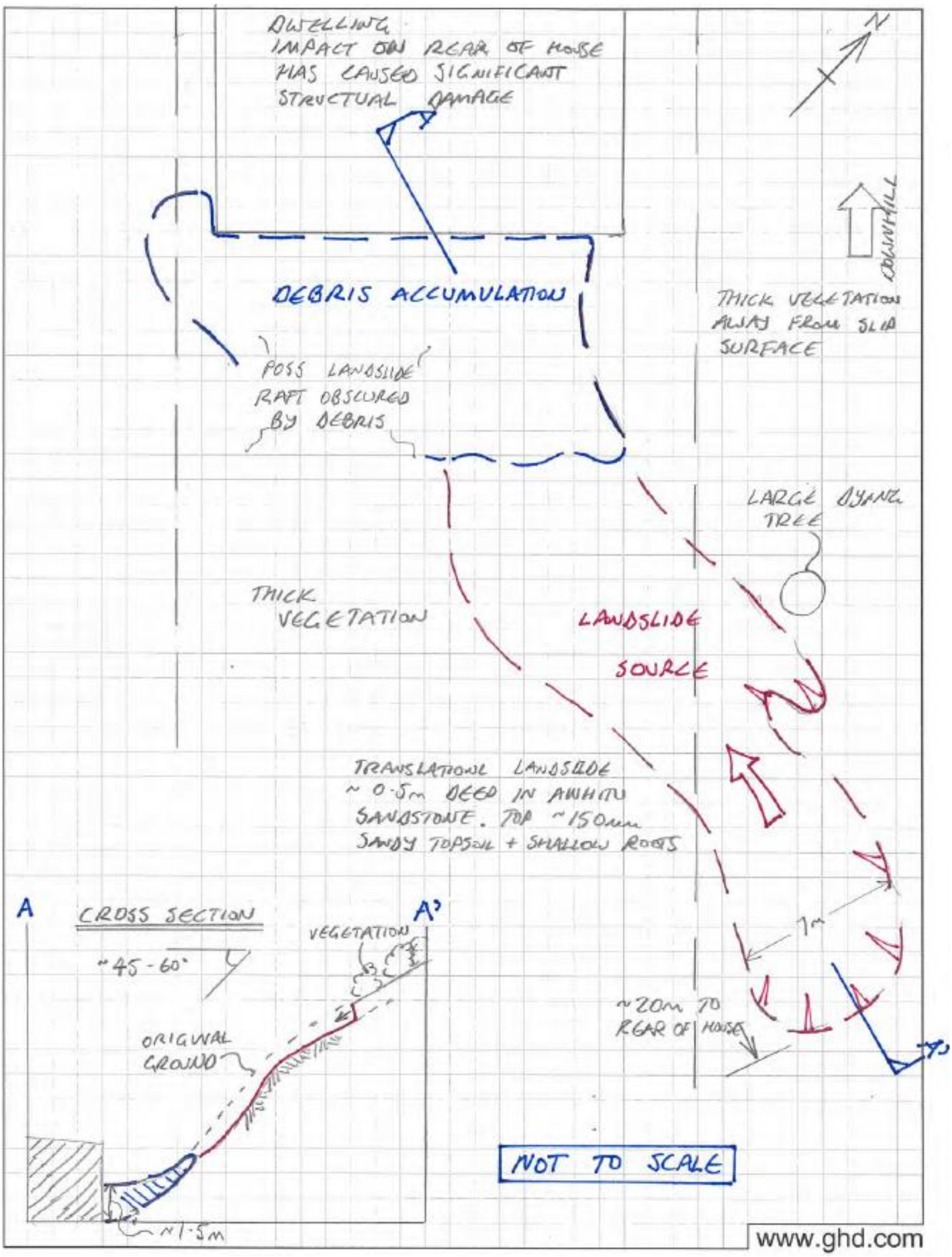


Figure 2.5 GHD site mapping of the landslide (completed 11 December 2023)

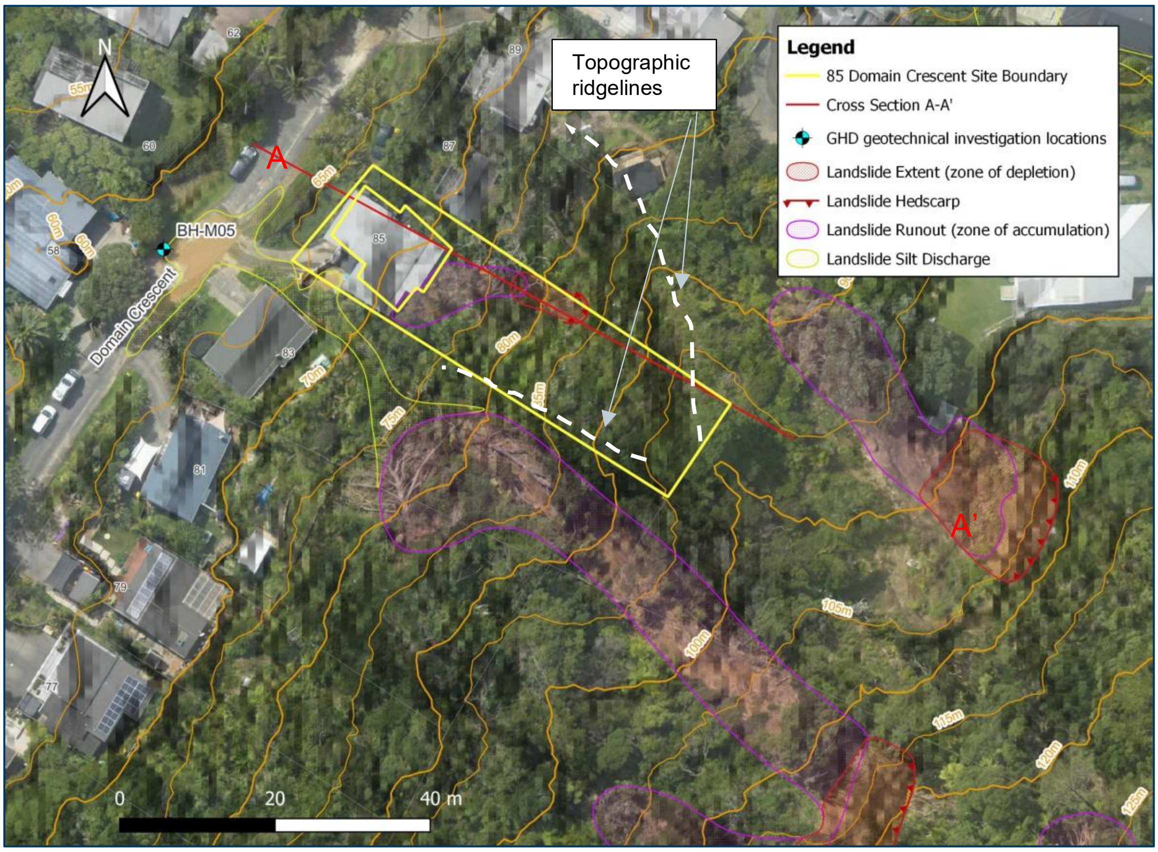


Figure 2.6 ***Landslide locations relative to the site shown on February 2023 aerial image.***

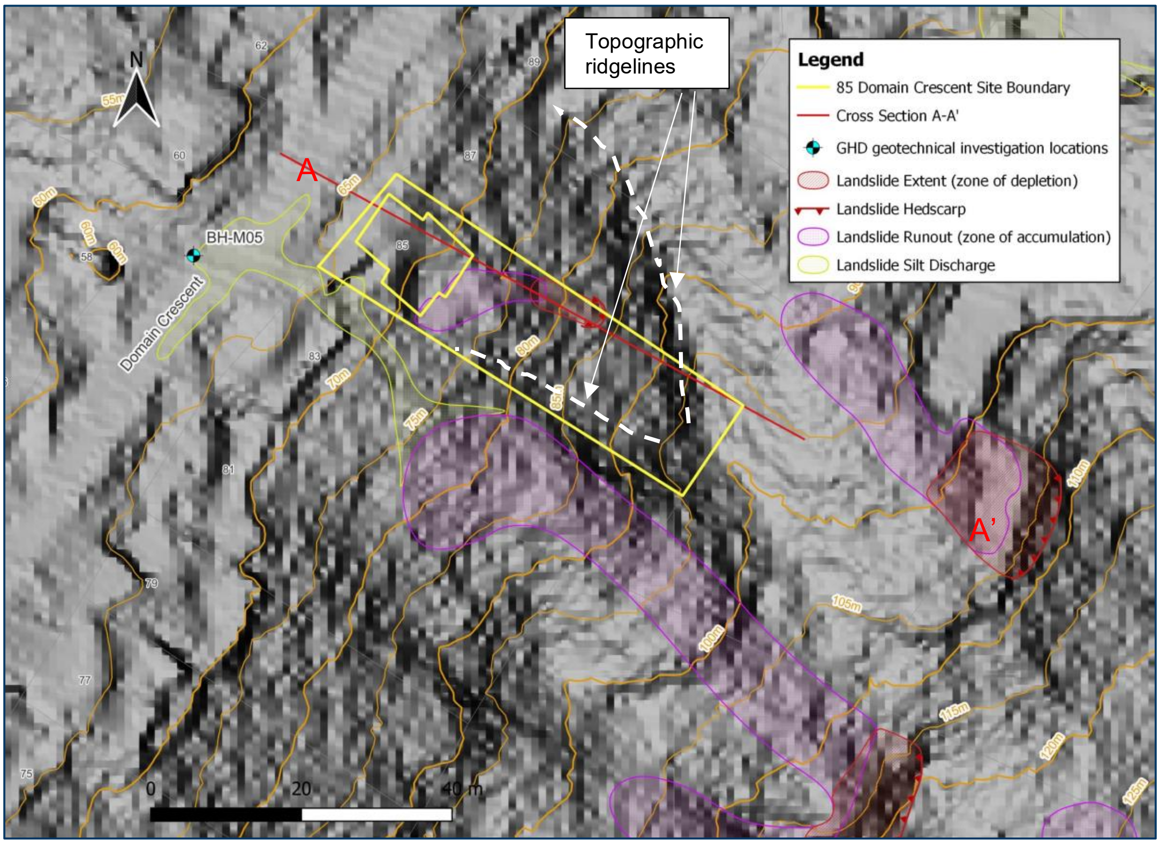


Figure 2.7 ***Landslide location relative to the site shown on LiDAR Hillshade (source: Auckland Council Feb 2023).***

Figure 2.8 **Exposed headscarp of landslide.**

Figure 2.9 **Failure surface (evacuated zone) exhibiting evidence of post failure erosion. Looking upslope.**

Figure 2.10 ***Debris piled up at the rear of dwelling (estimated up to 1.5 m thick)***

Figure 2.11 ***Damage caused by landslide includes racking of entire building (exhibited by bending of exterior wall)***

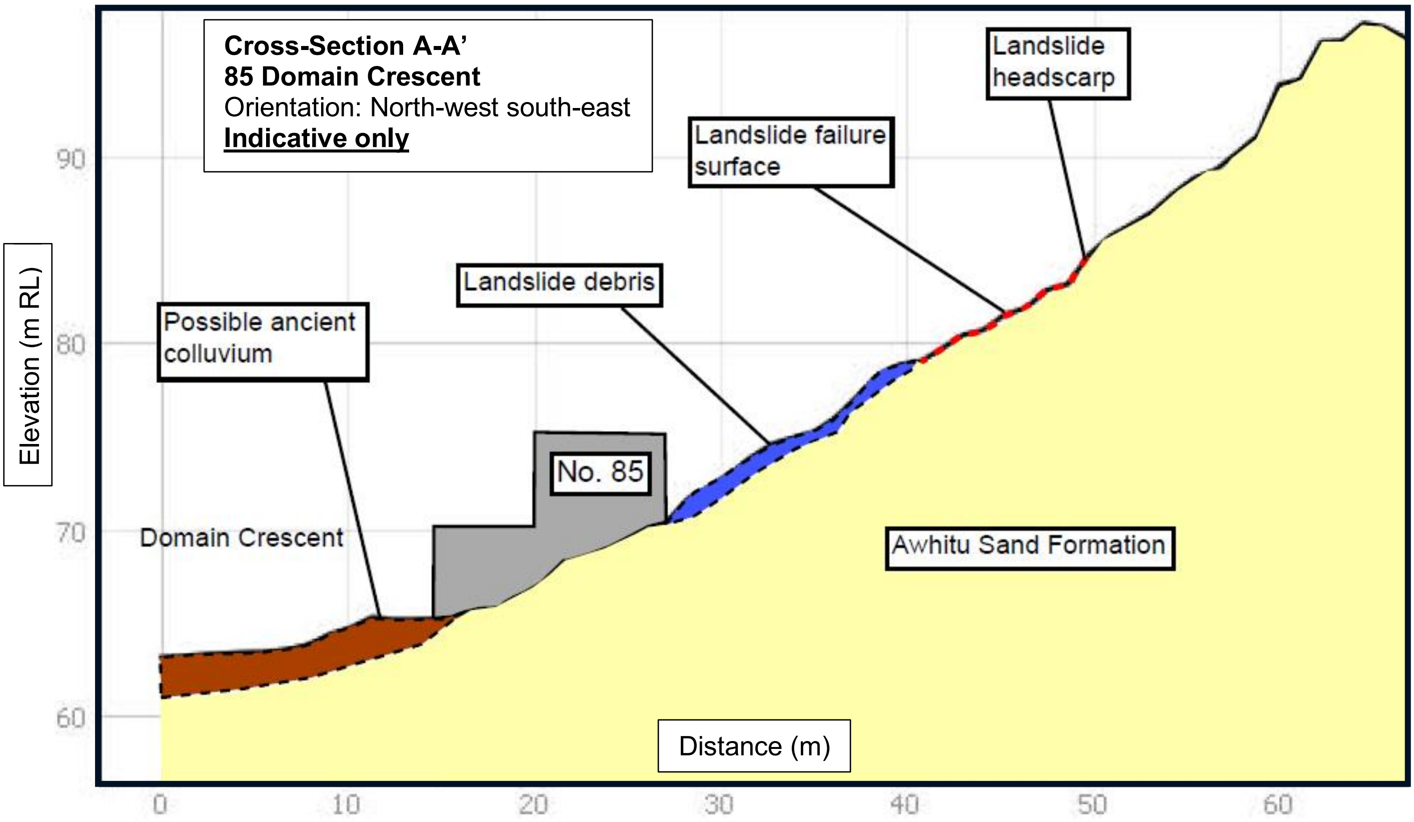


Figure 2.12 Indicative cross section A-A' through 85 Domain Crescent

3. Landslide risk estimation

The Australian Geomechanics Society Landslide Risk Management guidelines, published in 2007 and now commonly referred to as AGS (2007), have been adopted for the following unmitigated loss of life landslide risk assessment. Appendix A provides background information and guidance on how the methodology has been applied for assessing risk to life at the site.

The existing dwelling (or a new dwelling of similar construction occupying the same location) has been considered as the element at risk for this assessment. Our assessment assumes the recent landslide debris has been removed. Where appropriate, sensitivity checks have been undertaken for comparative purposes.

3.1 Hazard characterisation

The landslide hazards considered as part of this assessment are as follows:

- **LS1** (Landslide Hazard 1) – The most likely future landslide to occur somewhere on the slopes above the property. The landslide would be a shallow failure with a volume in the order of 40 m^3 that develops into a debris flow entraining additional downslope material. The assumed landslide characteristics have been inferred from observations of the previous failure and landslides to occur elsewhere in Muriwai. The possible source area considered for a future landslide above the dwelling, highlighted on Figure 3.1 and Figure 3.2 below, is constrained by two relatively prominent ridgelines.
- **LS2** (Landslide Hazard 2) – Regression of the existing landslide headscarp. This is likely to have a volume somewhat smaller than the landslide that occurred in February 2023.

3.2 Likelihood of landsliding ($P_{(H)}$)

The basis for estimating probability of occurrence for each landslide hazard considered as part of this assessment in provided in Appendix A and the probabilities adopted are provided below.

3.2.1 Likelihood of LS1

Two considerations of probability for occurrence for the most likely future landslide are:

- $P_{(H'1)}$ is the probability that the rainfall threshold for the most likely significant landslide is exceeded, which is taken as a proxy for landslide initiation. This is assumed to be 1 in 100 or **0.01** (see analysis by AC in Appendix A) or 1 in 50 or **0.02** under the influence of future climate change.
- $P_{(H'2)}$ is the probability that a slope above the dwellings fails. A single landslide occurred on the slopes above the dwelling. Considering the total area of the slopes above the dwelling with similar conditions, and therefore considered susceptible to failure, an estimate of 5% failed during the February 2023 rainfall event. Given that a significant portion of the possible source area is directly above the dwelling, an increased value of $P_{(H'2)}$ **= 0.1** has been adopted.

3.2.2 Likelihood of LS2

Given the current condition of the exposed landslide headscarp, it is considered that regression of the existing landslide will occur in the same location during a relatively frequent rainfall event. A value of $P_{(H'1)}$ of **1 in 10** or **0.1** is adopted whilst $P_{(H'2)}$ is considered certain and a value of **1.0** is adopted.

3.3 Probability of spatial impact ($P_{(S:H)}$)

Our estimate of spatial probability is based on several factors which depend on the landslide hazards being considered and site-specific slope conditions. Our approach is detailed in Appendix A. Figure 3.1 and Figure 3.2

below provide an indication of the slope conditions at 85 Domain Crescent and the surrounding area (slope angles and inferred preferential flow paths, respectively).

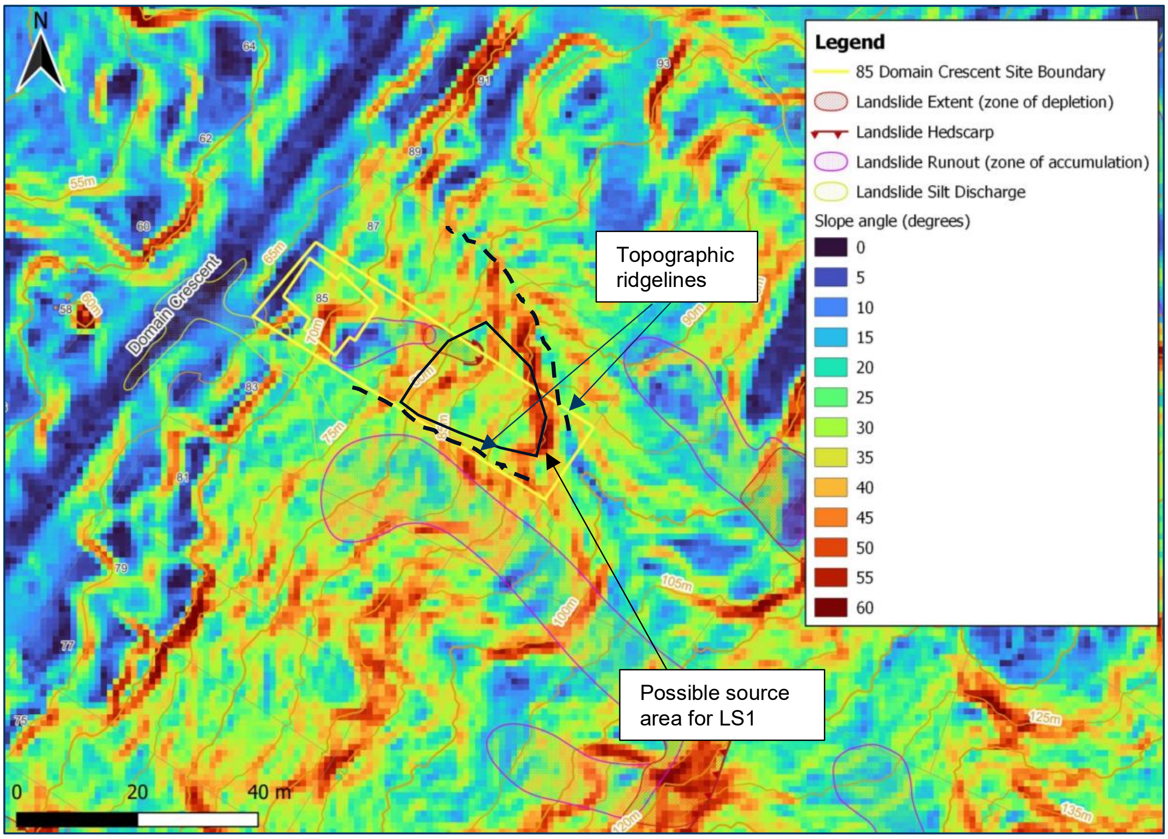


Figure 3.1 *Slope map of 85 Domain Crescent and surrounding area. Slope angles based on 2023 DTM data.*

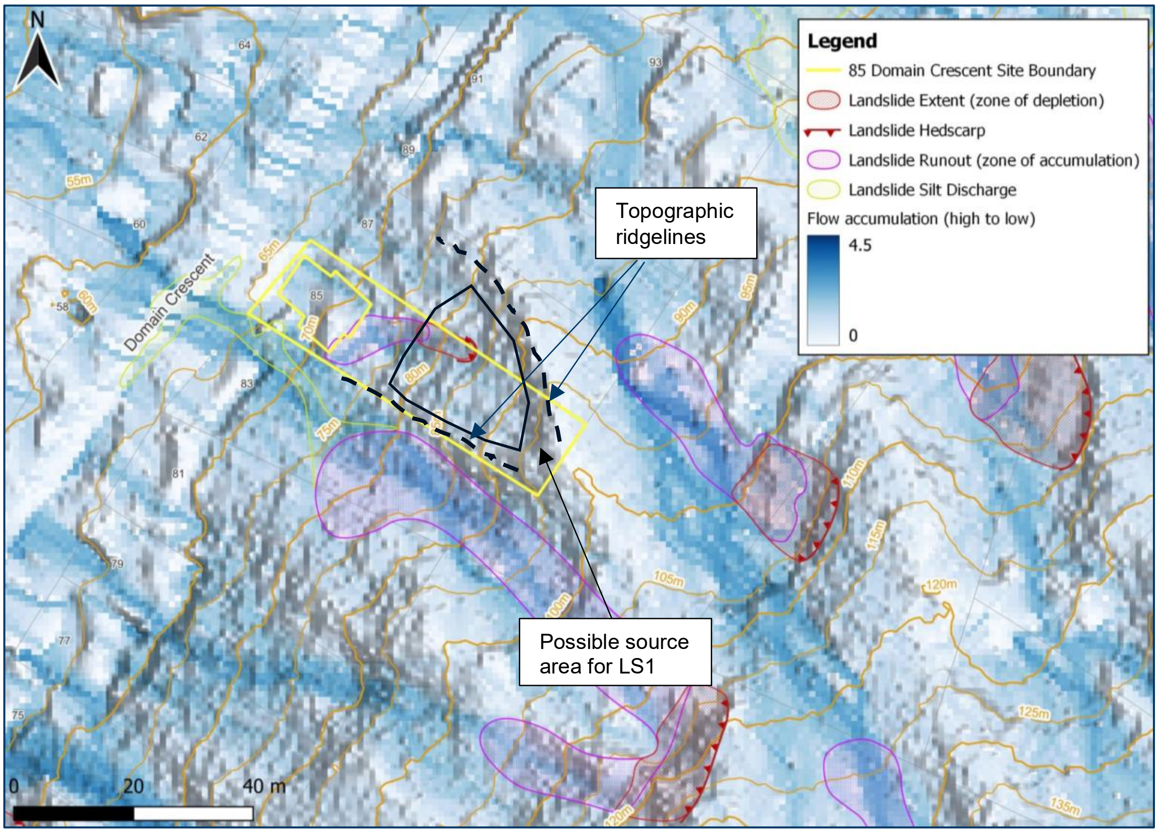


Figure 3.2 *Flow accumulation map of 85 Domain Crescent and surrounding area. Indicates preferential flow path for surface water. Modelling based on 2023 DTM data.*

3.3.1 Probability of spatial impact (LS1)

Two conditional factors are considered for the most likely significant landslide:

- $P_{(S':H'1)}$ is the probability that if the landslide occurs it travels in the direction of the site. Based on the position of the dwelling at the base of a relatively planar slope exhibiting a somewhat concave geomorphology at its crest, a landslide initiating in the possible source area above the site (Figure 3.1) would likely travel downslope (northwest) towards the dwelling. Based on the flow accumulation plot (Figure 3.2) a landslide is unlikely to take a preferential flow path. A value of **1.0** is adopted.
- $P_{(S':H'2)}$ is the probability that if the landslide occurs it will reach the property. The natural slopes above are generally steep (30-40°). Based on an approximate landslide volume of 40 m^3, an adopted travel angle of 35° (Appendix A methodology based on data from Piha and Karekare) would project the landslide to the rear of the dwelling. Empirical methods in the GHD (2023) Muriwai risk assessment report indicate that, based on a downslope angle of approximately 35°, the predicted travel distance angle would be approximately 30° (for an unconfined travel path). This values also generally agrees with published data in Hunter & Fell (2002). This would project the landslide beyond the dwelling. A probability value of **1.0** has been adopted as a conservative approach.

3.3.2 Probability of spatial impact (LS2)

Landslide hazard LS2 involves upslope or lateral regression of the existing landslide.

- If the existing landslide hazard were to reactivate and result in regression of the headscarp, it is likely that the new landslide would follow the same path as the previous one, and hence travel towards the rear of the dwelling. As such a probability of **1.0** has been adopted for $P_{(S':H'1).}$
- Regression of the existing landslide is expected to result in mobilisation of a somewhat smaller volume of debris. Given the observed behaviour of the previous slide (impacting the rear of the dwelling) and the topography of the site, any future failure is judged certain to almost certain to reach the dwelling. As such, a value of **0.8** is adopted for $P_{(S':H'2).}$

3.4 Temporal spatial probability ($P_{(T:S)}$)

As discussed in Appendix A, a temporal spatial probability of **0.68** is the adopted value for each property and has been used in this assessment.

3.5 Vulnerability ($V_{(D:T)}$)

In the event a debris flow reaches the dwelling from the slopes above, the flow depth is likely to be in the order of 1.0 m. The flow is likely to have a higher volume and velocity than the previous landslide increasing the potential to result in inundation or partial collapse of the building. Given the extent of structural damage as a result of the previous landslide, a value of **0.8** is adopted for LS1.

In the event that regression of the existing landslide occurs on the slope above the dwelling, it is expected that debris would impact the rear of the dwelling but not result in building collapse. Based on the vulnerability table in Appendix A, a value of **0.1** is adopted for LS2.

3.6 Unmitigated Risk Estimation

A summary of the risk estimation for each conceivable landslide hazard is presented in Table 3.1 below. A sensitivity check assuming a higher probability of occurrence for $P_{(H)}$ is included for comparative purposes.

Table 3.1 ***Summary of unmitigated risk estimation for each hazard type by domain.***

Hazard	**Annual probability of the landslide** $P_{(H)} = P_{(H'1)}$ x $P_{(H'2)}$	**Spatial probability** $P_{(S:H)} = P_{s':H'1)}$ x $P_{(S':H'2)}$	**Temporal probability** $P_{(T:S)}$	**Vulnerability** $V_{(D:T)}$	**Risk** $R_{(LOL)}$	**Risk evaluation***
LS1 ***(most likely future landslide hazard)***	**0.01 x 0.1**	**1.0 x 1.0**	**0.68**	**0.8**	**5.4 x 10^{-4}**	**Not tolerable**
LS1 *Sensitivity check*	*0.02 x 0.1*	*1.0 x 1.0*	*0.68*	*0.8*	*1.1 x 10^{-3}*	*Not tolerable*
LS2 ***(regression of existing landslide hazard)***	**0.1 x 1.0**	**1.0 x 1.0**	**0.68**	**0.1**	**6.8 x 10^{-3}**	**Not tolerable**
LS2 *Sensitivity check*	*0.2 x 1.0*	*1.0 x 1.0*	*0.68*	*0.1*	*1.4 x 10^{-2}*	*Not tolerable*

**The evaluation is a guide only based on recommendations from AGS (2007) which provides a suggested tolerable Loss of Life Risk for the person most at risk.*

We acknowledge that assessing risk has an inherent degree of uncertainty and may only be accurate to within half an order of magnitude. This level of uncertainty would not change the outcome of the analysis. Refer to Appendix for further discussion.

4. Conclusion and recommendation

This report has presented the results of a quantitative risk assessment for unmitigated loss of life in relation the property located at 85 Domain Crescent, Muriwai, Waitākere. Two landslide hazards (LS1 and LS2) have formed the basis of this assessment.

Assessment of the most likely future landslide (LS1) estimates the annual risk to loss of life for the person most at risk to be approximately **5.4 x 10^{-4}**. This risk is higher than the AGS (2007c) suggested tolerable Loss of Life Risk for the person most at risk (see Appendix A).

Assessment of the failure of the existing landslide hazard (LS2) estimates the annual risk to loss of life for the person most at risk to be approximately **6.8 x 10^{-3}**. This risk is significantly higher than the AGS (2007c) suggested tolerable Loss of Life Risk for the person most at risk (see Appendix A).

Potential remedial measures to lower the risk level from the existing landslide hazard (LS2) may be possible. However, identifying such measures is outside of the scope of this study.

As discussed above, this report considers geotechnical matters only. There may be other non-geotechnical considerations that affect final placard designation of which GHD are not aware, such as flood risk and structural damage to property.

We understand AC are currently reviewing their tolerable and acceptable risk criteria for risks associated with landsliding. We recommend Council review the risk assessment presented in this report against the AC risk criteria to assess whether it is appropriate to assess the property risk categorisation and remove or re-assess the current placard designation for the site.

5. Limitations

This report has been prepared by GHD for Auckland Council and may only be used and relied on by Auckland Council for the purpose agreed between GHD and Auckland Council as set out in section 1.2 of this report.

GHD otherwise disclaims responsibility to any person other than Auckland Council arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

The opinions, conclusions and any recommendations in this report are based on assumptions made by GHD described in this report (refer section 1.2 of this report). GHD disclaims liability arising from any of these assumptions being incorrect.

An understanding of the geotechnical site conditions depends on the integration of many pieces of information, some regional, some site specific, some structure specific and some experienced based. Hence this report should not be altered, amended, abbreviated, or issued in part in any way without prior written approval by GHD. GHD does not accept liability in connection with the issuing of an unapproved or modified version of this report.

Verification of the geotechnical assumptions and/or model is an integral part of the design process - investigation, construction verification, and performance monitoring. If the revealed ground or groundwater conditions vary from those assumed or described in this report the matter should be referred back to GHD.

This risk assessment does not mean that there will be no further landsliding impacting this property or group of properties.

Appendix A

AGS (2007) Background

1. Overview

This appendix document outlines the methods and procedures used to estimate risks to loss of life for the person-most-at-risk at the site described in the covering report. This document should be read in conjunction with the covering report as it contains information not presented in the covering report. This document should not be separated from the main report.

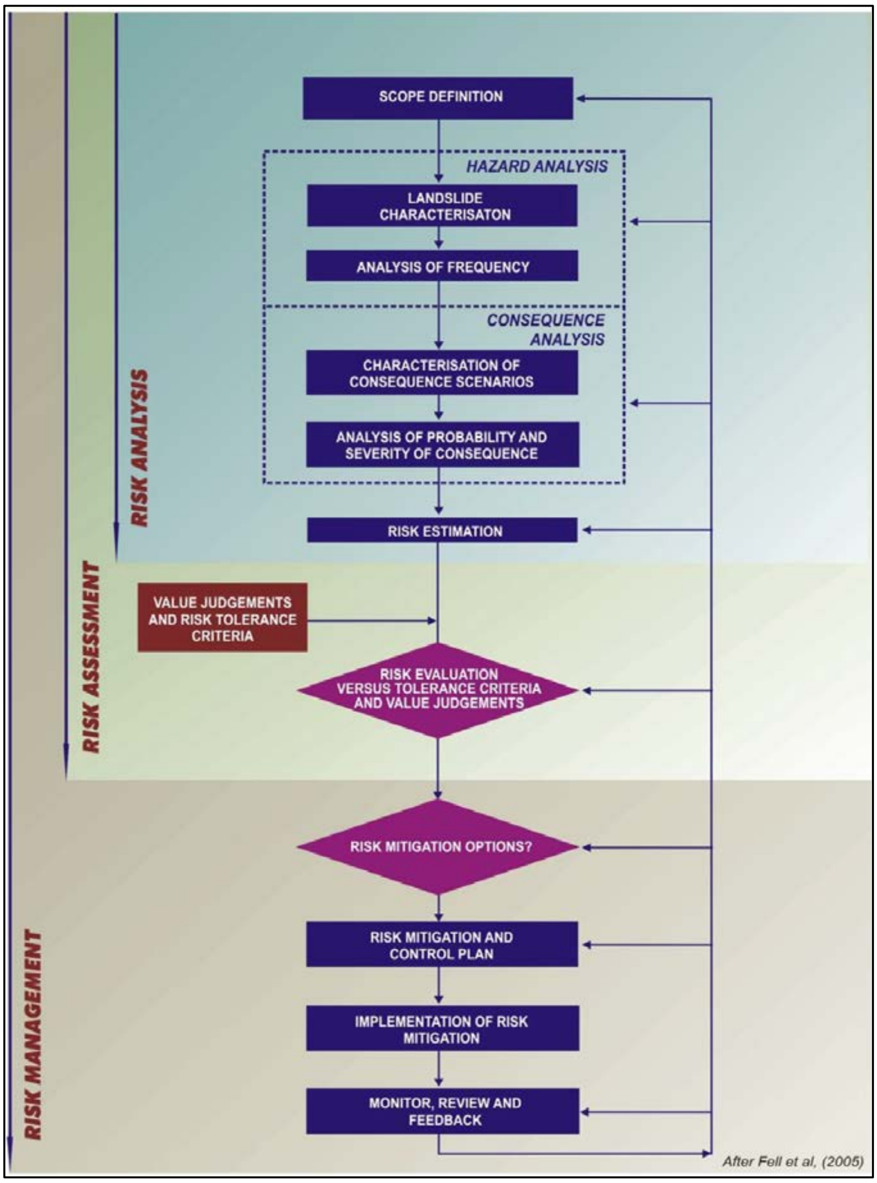
2. Landslide Risk Management Framework

2.1 Background

The 1998 Thredbo landslide, in which 18 persons were killed, highlighted the challenges faced from building upon steep slopes and led to the development of the Australian Geomechanics Society Landslide Risk Management guidelines, published in 2007 and now commonly referred to as AGS (2007). The suite of guidelines is recognised nationally (Australia) and internationally as world-leading practice. The reader of this report is encouraged to consult the freely available LRM resources which can be accessed at: https://landsliderisk.org/.

The ”Practice Note Guidelines for Landslide Risk Management” (AGS 2007c), provide technical guidance in relation to the processes and tasks undertaken by geotechnical practitioners who prepare LRM reports including appropriate methods and techniques. The Practice Note is a statement of what constitutes good practice by a competent practitioner for LRM, including defensible and up to date methodologies and provides guidance on the quality of assessment and reporting, including the outcomes to be achieved and how they are to be achieved.

The framework for landslide risk management is presented in the figure below and represents a framework widely used internationally.



After Fell et al, (2005)

Figure A1 Framework for landslide risk management.

2.2 Risk Estimation Methodology

AGS (2007c) requires risks to loss of life to be estimated quantitatively for the person-most-at-risk. The person-most-at-risk will often but not always be the person with the greatest spatial temporal probability (i.e. the person most exposed to the risk). The Individual Risk-to-Life is defined as the risk of fatality or injury to any identifiable (named) individual who lives within the zone impacted by the landslide; or who follows a particular pattern of life that might subject him or her to the consequences of the landslide. The risk of 'loss-of-life' to an individual is calculated from:

$$\mathbf{R}_{(LoL)} = \mathbf{P}_{(H)} \times \mathbf{P}_{(S:H)} \times \mathbf{P}_{(T:S)} \times \mathbf{V}_{(D:T)}$$

Where:

$\mathbf{R}_{(LoL)}$ is the risk (annual probability of death of an individual).

$\mathbf{P}_{(H)}$ is the annual probability of the landslide (event).

$\mathbf{P}_{(S:H)}$ is the probability of spatial impact of the event impacting an individual taking into account the travel distance and travel direction given the event. For example, the probability of an individual in a building or in the open being impacted by a rockfall / landslide at a given location.

$P_{(T:S)}$ is the temporal spatial probability (e.g. of the building or location being occupied by the individual at the time of impact) given the spatial impact and allowing for the possibility of evacuation given there is warning of the event occurrence.

$V_{(D:T)}$ is the vulnerability of the individual (probability of loss of life of the individual given the impact).

2.3 Landslide Risk Assessment Uncertainty

The process of risk assessment involves estimation of likelihood, consequence and risks based on available information for the study site. By its very nature, much of the data, including historical and current inventories may be incomplete whilst an understanding of the triggering events has a degree of uncertainty attached to it. Judgement is required to estimate the nature and size of potential hazards, their frequency of occurrence and their impact on a variety of elements at risk. As these judgements are based on the knowledge, experience and understanding of the assessor, it is not unusual for different assessors to make different judgements about the level of risk.

The thought process used in establishing likelihoods, consequences and determining spatial and temporal factors for properties has been documented for transparency. The structure of the risk assessment process is well defined and values for some input parameters have been tabulated to guide standard approaches by different assessors. However, this should not be mistaken for precision given the limitations of the inputs outlined above. Generally, the levels of likelihoods and risks should be thought of as being within a range of typically +/- half an order of magnitude.

While the basis for the judgements contained in this report are well documented, and the levels of risk considered to be good representations of reality, the accuracy and precision of the process should not be overestimated and should always be used in an appropriate manner in combination with risk management including mitigation and treatment options.

3. Hazard Characterisation

AGS (2007c) generally states that all credible hazards originating on, above and below the sites should be assessed. This is generally a predictive exercise based on knowledge and understanding of the geological and geomorphological setting with a view to assembling historical evidence for past hazard events.

3.1 Defining the Most Likely Significant Landslide

Following Cyclone Gabrielle, small landslides within the Muriwai area were often noted to be shallow translational slides developed in the upper residual profile of the Awhitu Sand Formation which, under saturation, transition into debris flows. Detailed analysis by GHD of the mapped landslides within the Karekare and Piha areas, which included size, estimated volume, travel distance and travel angle, was undertaken to characterise the nature and distribution of landslides following the rainfall events that occurred in early 2023, particularly the Cyclone Gabrielle rainfall event, has been used as a basis for defining the magnitude of the ‘most significant landslide’ for the site.

A total of 80 landslides were mapped throughout Karekare and Piha following the storm events in Jan and Feb 2023. These landslides were then grouped into categories of volume in 50 m^3 increments. Results for an assessment of “frequency as categorised by volume” is shown in Figure 1 below.

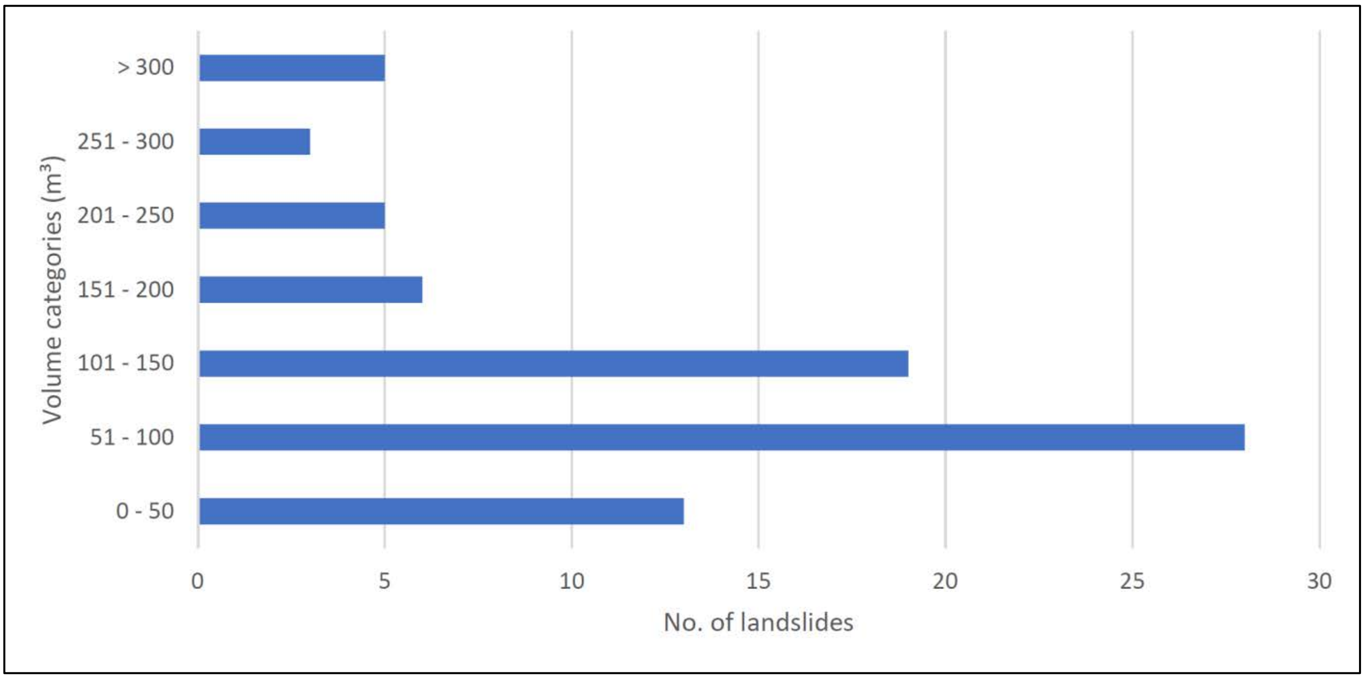


Figure A2 *The number or frequency of mapped debris flows (on the x axis) as categorised by volume increments for mapped source areas of debris flows (on the y axis in m^3) in Karekare and Piha.*

In addition, detailed information regarding volume size, travel angle, travel distance, confinement (either unconfined or channelized) and the degree of damage caused by slides impacting dwellings and building was also collated and a number of additional graphs were developed as below:

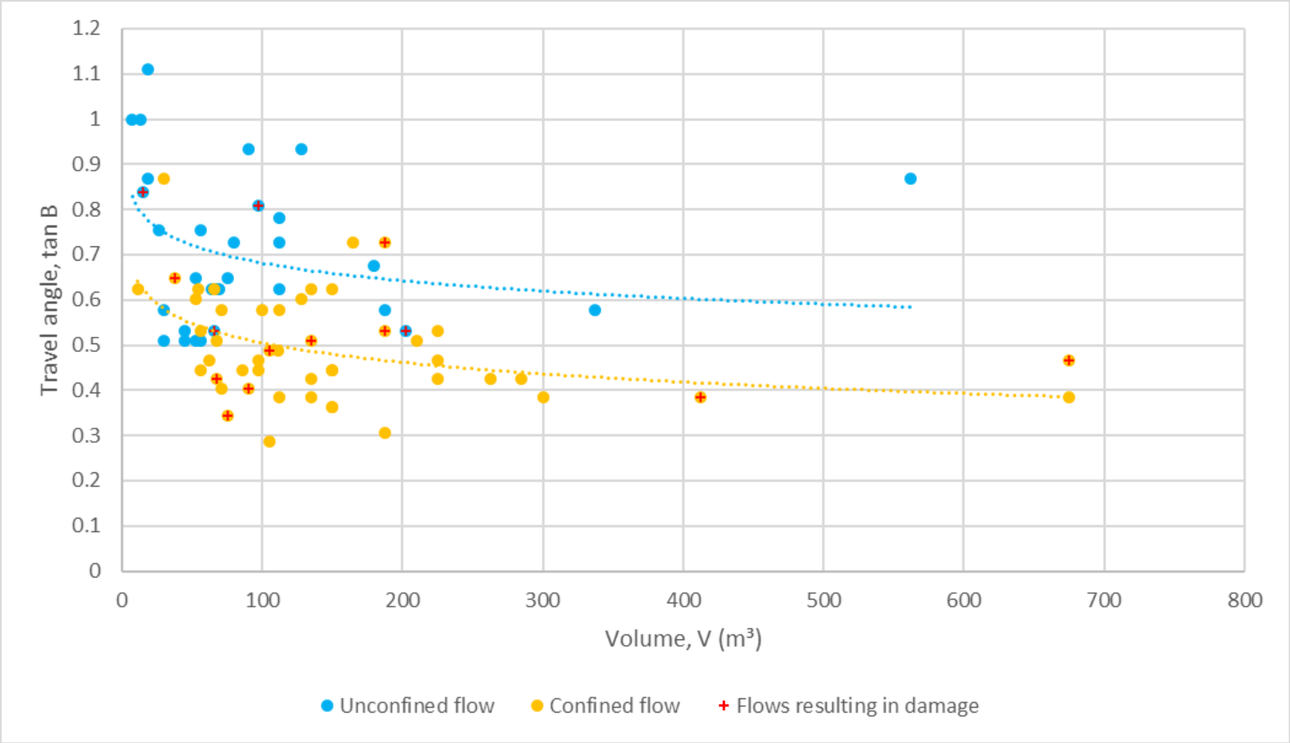


Figure A3 *Travel angle vs volume of source area for the Karekare and Piha debris flows*

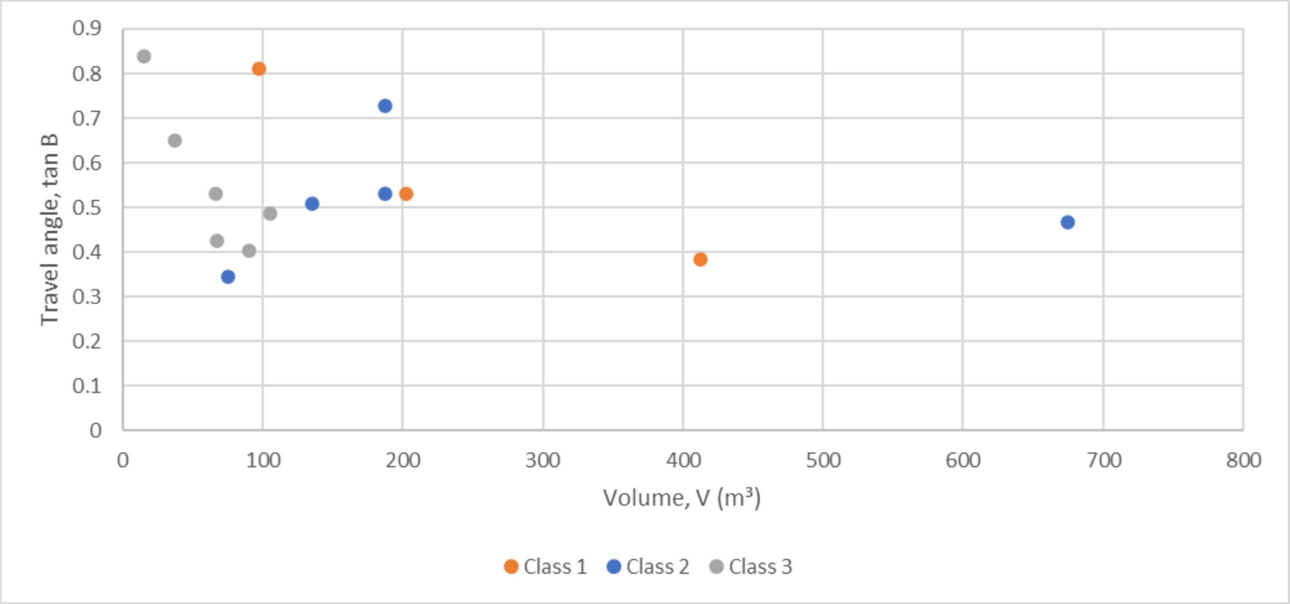


Figure A4 ***Plot of only those debris flows known to have caused some degree of damage to dwellings and buildings. Note Class 1 = Complete destruction/collapse of building, Class 2 = Partial destruction/collapse of building, significant inundation and Class 3 = Limited damage to building but no collapse or inundation, damage is other property infrastructure e.g., access stairs.***

This assessment highlights a number of important points relating the nature of these hazards including:

- Whilst a range of volumes of source areas for debris flow was noted, the most common or likely sized event was of the order of 50-100 m^3 as determined by the frequency plot.
- Many smaller volume source areas for debris flows (less than 75 m^3) typically only caused some lesser damage to buildings but once the volume increased above 100 m^3, then the vast majority of debris flows were noted to have caused partial or full collapse of dwellings and buildings.
- The greater the volume of the source area, the lower the travel angle and the greater the runout or travel distance.
- Unconfined debris flows generally have a higher travel angle compared to confined or channelized debris flows of the same volume. This means that confined or channelised debris flows have a longer runout or travel distance and hence have more potential to impact elements at risk further down the slope.

Based on this site-specific data and analysis, GHD has adopted a working definition for these risk assessments of what is termed the **most likely significant landslide** as follows:

- The volume of most likely significant landslides is assumed to be 100 $m^{3.}$
- This volume has been shown to cause significant building damage resulting in partial to full dwelling and building collapse.
- As a result, this hazard is considered to have a high probability for causing loss of life.
- Where this hazard is unconfined, the adopted travel angle based on Figure 3 has been taken as Tan (B) = 0.69 or approx. = 35°
- Where this hazard is confined or channelised the adopted travel angle based on Figure 3 has been taken as Tan (B) = 0.50 or approx. = 26.5°
- Comparison with Figure 6 from Hunter and Fell (2002) suggests the site derived travel angles are generally consistent with other data presented in that plot.

The definition of the **most likely significant landslide** is considered to be a reasonably conservative but not overly cautious estimate of the potential hazard that may affect the site. This is based on an assessment of an overview of landslides that GHD has observed in Muriwai, Karekare and Piha in 2023.

It is noted however that in some specific circumstances, larger recent debris flows may have occurred in close proximity to the site under investigation. As such, where there is evidence for a larger hazard, the assessor may

choose to adopt a larger volume event based on judgement and knowledge of that particular site. In this case other values for travel angle can be read from Figure 3.

IMPORTANT NOTE: It is duly acknowledged that volume alone does not necessarily account for the full potential of a debris flow to cause significant damage and other factors such as the degree of channelization, the additional entrainment of volume within a channel, the degree of saturation of the debris materials, the location of the source area on the hillslope, the direction of travel, the distance of travel and the velocity of the hazard at the point of impact all play important roles in the destructive capacity of any debris flow. Some of these factors are considered within the risk assessment process as conditional probabilities in spatial considerations.

3.2 Description of Other Landslide Types

As discussed in the scope of the covering report, other landslide hazards may exist at the site under assessment. These may include existing geohazards that have resulted from recent failures with the potential to pose risk to life in the immediate short-term (i.e. within the next few years) such as regression of translational failures to occur downslope of dwelling, failure of over-steepened fill and cut slopes, rockfall hazards associated with exposed rock faces/headscarps and/or loose debris remaining upslope of dwellings.

In addition, other possible geotechnical slope instability hazards relating to modified slopes (i.e. human made) may also exist and have potential to pose a risk to life - such as failures of fills, cuttings and failed retaining walls. This represents hazards that may have a range of likelihood from almost certain to possible.

Where appropriate, descriptions and definitions for each of these hazards are provided in the covering report on a case-by-case basis and will be specific to the observed hazard and actual conditions at this site.

3.3 General Descriptors for Size Classification of Landslides.

Generalized or relative descriptions of size classification systems for landslides vary significantly depending on the country of origin and the nature of the landslide hazards typically encountered. For the purposes of these assessments, GHD proposes to use the following size classification descriptions adopted from the Transport for New South Wales (TfNSW) Guide to Slope Risk Analysis Version 4 (TfNSW 2014) (see Table 3.1 below).

Table A3.1 Landslide size classification

Relative size term	Volume range	Typical mid-range dimensions (width x length x depth in metres)
Very small	<20 m3	4 x 4 x 0.5
Small	20 to 200 m3	10 x 10 x1
Medium	200 to 2000 m3	20 x 20 x 2.5
Large	2000 to 20000 m3	40 x 40 x 5
Very large	>20,000 m3	60 x 60 x 8

4. Likelihood $P_{(H)}$

Likelihood or annual probability of occurrence of the landslide, $P_{(H)}$, is one of the most critical but difficult to estimate factors as part of the risk assessment process.

4.1 The Most Likely Significant Landslide

The recent flood / storm events, the estimation of recurrence intervals for that event and the occurrence of the observed hazards form the basis for the current estimated probability of occurrence for the most likely significant landslide hazard. However, observations of the recent events noted that not all similar slopes failed as a result of

the initiating storm event and as such, an additional consideration for probability of occurrence has been included within the analysis by using conditional probabilities as follows:

$$P_{(H)} = P_{(H'1)} \times P_{(H'2)}$$

Where:

$P_{(H'1)}$ = Probability that the rainfall threshold for the most credible significant landslide is exceeded which is taken as a proxy for landslide initiation. This is assumed to be 1 in 100 or 0.01 (see analysis and discussion by Auckland Council below) or 1 in 50 or 0.02 under the influence of future climate change.

$P_{(H'2)}$ =Probability that the slope for the specific assessment fails, which relates to how many of the actual slopes failed out of the total number of all slopes present. This probability is typically based a on spatial analysis of the total area of failed landslides slopes compared to the total area of all slopes for the geomorphic setting in which the site is located.

4.2 Auckland Council Guidance on Frequency for Most Likely Significant Landslide

Council provided GHD with an assessment of available rainfall data associated with Cyclone Gabrielle (Auckland Council 2023) (AC memo). During Cyclone Gabrielle, the tipping bucket rain gauge at Muriwai failed and was inundated by flood waters. The AC memo also provided rainfall analysis using AC's Quantitative Precipitation Estimate (QPE) Rain Radar System, which is a real-time rainfall product that utilises the MetService radar. The rainfall data presented by AC indicates a peak rainfall total for Muriwai during the event of 146.9mm, occurring over 12-hour period. This total is >100-year event at a 12-hour duration. The data suggests that for the 12-hour duration rainfall, the Annual Recurrence Interval (ARI) is >100 years and may be in the order of 250 years. However, we understand that the calculation above the 100-year assessment becomes increasingly unreliable, primarily as a result of the relatively short statistical rainfall records available in New Zealand. For the other durations modelled, the rainfall was below the 100-year event.

The AC memo recommended that an envelope of "risk" is estimated as the ARI figures will change over time and as these events are incorporated into the statistical record. The AC memo states that in general, it is considered reasonable to consider the Cyclone Gabrielle event to be in the range of 100-250 year ARI. For this assessment we have assumed that the annual likelihood of a landslide event occurring that is similar in magnitude to the February 2023 event, is about 1 in 100 (i.e., 0.01). This is considered to have a *likely* probability of occurrence.

The assumption of 1 in 100 based on rainfall frequency is a simplifying and possibly conservative assumption that we consider reasonable. It does not consider other factors that could potentially affect stability (antecedent conditions, geology, groundwater conditions, slope height and angle, vegetation, surface water management-overland flow path, overflow from water storage tanks, effect of effluent disposal field), all of which are difficult to quantify.

The AC memo further recommended that risk assessment reports consider the potential for climate change to increase the frequency of high intensity rainfall. We understand that the National Institute of Water and Atmospheric Research (NIWA) has projected a 20% increase in rainfall intensity over the next 100 years which suggests that a 250-year ARI event could increase to a 50-year ARI event. Consequently, we have also included a sensitivity check based on a 50-year ARI event.

We draw the reader's attention to Section 3 of this report and reiterate that AGS (2007c) generally states that all credible hazards originating on, above and below the sites should be assessed. This report has conformed to this requirement and assessed landslide hazards that were observable during the site mapping and/or able to be interpreted via other means such as readily available aerial photographs, lidar data etc. It should be recognised that specific hazards such as rockfalls, failed retaining walls, over-steepened cuts/fill batters may have likelihoods in the *Certain to Almost Certain* range and are more likely to occur in the short term.

4.3 Other Landslide Hazards

Where other slope failures and instabilities as described in Section 3.2 are considered, individual assessments of $P_{(H)}$, the probability of occurrence, are made on the basis of expert judgment, performance of similar landslides in the area and recent site observations.

When considering hazards that may pose immediate or short-term risks to life it is probable that such hazards will have high likelihoods of occurrence that could be triggered by relatively frequent events. As a result, such hazard may have likelihoods in the *Certain to Almost Certain* range as per the ASGS2007 qualitative descriptors for likelihood.

5. Probability of Spatial Impact $P_{(S:H)}$

The AGS definition of spatial probability is represented by single term $P_{(S:H)}$ and is described as the probability of spatial impact by the landslide on the element at risk, given the landslide occurs and taking into account the travel distance and travel direction.

5.1 The Most Likely Significant Landslide - Upslope of Site

A number of conditional factors may be involved in the spatial distribution for the most likely significant landslide, and for further transparency, the following methodology has been adopted:

$$P_{(S:H)} = P_{(S':H'1)} \text{ x } P_{(S':H'2)}$$

Where:

- $P_{(S':H'1)}$ = The probability that if the landslide occurs it travels in the direction of the site under assessment. If the slopes above are consistent, and planar then probability is assumed to be 0.8 to 1.0 depending on the topography; if the originating landslide enters a channel that is directed onto the property then probability is assumed to be 1.0, or if the landslide enters a channel that is directed away from the sites then the probability is assumed to be 0.05 taking account of a small probability that the landslide may super elevate and leave the channel.
- $P_{(S':H'2)}$ = The Probability that if the landslide occurs it will travel to at least the site under assessment and will impact the property. This is to be based on two considerations as follows:

1. Modelled Behaviour based on travel distance analysis undertaken by GHD for 80 observed landslides slides in the Karekare and Piha areas (see Figure A3). Either probability = 1.0 if the travel angle projects past the dwelling, = 0.5 if the travel angle projects to the rear of the dwelling or = 0.0 if the travel angle falls short of the dwelling.

And/or

2. Observational behaviour: based on site observations of whether the previous landslides within close proximity to the study site, travelled sufficient distance to reach the site under assessment; if yes Probability = 1.0, if no, then probability = 0

- NOTE 1: The GHD analysis of travel distance highlights the effect of channelisation which shows confined debris flows travel further (i.e., they have a lower travel angle) than those which are unconfined on consistent or planar slopes. Such considerations are included on a site-by-site basis. Interestingly, this event-specific analysis also generally agrees with findings presented in Hunter and Fell (2002).
- NOTE 2: Where significant debris flows have occurred in close proximity to the site under assessment, and the observed travel distance is greater than that estimated using the modelled approach, the preferred GHD approach is to use the greater of the two travel distances to assess spatial impact.

5.2 The Most Likely Significant Landslide – Under the Dwelling/Building and/or Downslope Below the Dwelling/Building

Based on the possible failure area:

- If the failure area is > ~5 m from the dwelling then the value for $P_{(S:H)}$ will be 0 as a landslide occurring at that location will not impact dwelling. (The general assumption is that the landslide headscarp would have a length of 5m based on size of most likely significant landslide).
- If the failure area is within ~5m from the dwelling (like above) then the value for $P_{(S:H)}$ will be 0.5 to account for uncertainty of it encroaching within the footprint of the dwelling.
- If the failure area encompasses a significant portion of the dwelling then the value for $P_{(S:H)}$ will be 1.0 as there is a certain probability it will impact the dwelling.

Estimates of how far back the most significant landslide will regress are difficult to model without a detailed slope stability analysis and sufficiently accurate soil and rock inputs. This would require an intrusive geotechnical investigation which is outside the scope of this study.

GHD has adopted a more empirical approach that assesses the spatial extent of lateral downslope movement of the most likely significant landslide based on direct observations of existing landslides in close proximity to the site under assessment. In the absence of other information, a similar extent of regression has been applied to any future slides. An estimate of $P_{(S:H)}$ can then be made as to the potential interaction with the element at risk.

5.3 Other landslides – Upslope of the study site

Other types of potential landslides situated above dwellings and buildings on the site under assessment, should be assessed in a similar manner to the most likely significant landslide. Estimates of travel distance are taken from Hunter and Fell (2002) and/or previous local knowledge and/or observation of similar landslides in the area.

When undertaking short term assessments, hazards involving reactivation of existing landslides that are located upslope of the study site that didn't previously reach the site must be taken account. In addition, remobilisation of debris from any upslope landslides must also be assessed for their potential of runout or travel distance using Hunter and Fell (2002).

Similarly potential failures of modified slopes such as cuttings or fills located above or directly adjacent to dwellings and buildings must also be assessed for their spatial impact and the methods of assessment follow the same approach.

5.4 Other landslides – under buildings and downslope of the building

A similar approach to that taken for other landslides upslope has been adopted. Observation of existing failures and how much lateral downslope movement can be used as a proxy for what may occur in the future under a regression type scenario.

5.5 Temporal Spatial Probability $P_{(T:H)}$

These risk assessments have not considered specific occupancy scenarios for each individual residence. We acknowledge that the occupancy of each residence could vary significantly depending on the demographics of the residents and the usage of the residence. For example, some residences may be predominantly used as holiday accommodation, occupied mainly on weekends, whereas other residences could be permanently occupied by working families.

This assessment has assumed the following occupancies:

- Residences are typically occupied for 15 hours each day during weekdays;
- On weekends, residences are occupied for about 20 hours each day;

– The percentage of time a residence is occupied is therefore about 68%.

Any further delineation of the spatial variations in occupancy (i.e. if a bedroom is at the front or the rear of the house etc) are not considered feasible or warranted within the context of the precision of this assessment.

6. Vulnerability $V_{(D:T)}$

6.1 Most likely significant Landslide

AGS (2007c) includes a table of vulnerability values for various inundation and building damage scenarios as adapted by Finlay et al (1999). It is important to note that the AGS (2007c) vulnerability table doesn't adequately cater for all the building damage scenarios GHD has observed in Muriwai, Karekare and Piha. GHD has therefore further adapted this table and combined it with information from the TfNSW Guide to Slope Risk Analysis (2014) as well as observations of damage to buildings and structures resulting from the recent landslides in Muriwai, Karekare and Piha.

The table of vulnerability values used in this assessment is presented in Table A6.1. These values have been used as a guide and expert judgement has been applied to select a value within the range of values where appropriate on a site-specific basis.

Table A6.1 Summary of Vulnerability Values adopted

Case	Range	Typical value to be used in this assessment	Comments
Person in a building that collapses under impact from debris flow	0.8 -1.0	0.9	Death is almost certain. Evacuation unlikely to occur
If building is inundated with debris and the person is buried	0.8 -1.0	0.8	Very high potential for death Evacuation unlikely to occur
If building is inundated with debris but no collapse occurs and the person is not buried	0.01 -0.1	0.1	High chance of survival Evacuation unlikely to occur
If the debris strikes the building only	0.001-0.05	0.01	Very high chance of survival
If failure occurs below the building and results in significant collapse	0.5-0.8	0.6	Moderate to high potential for death. No forewarning signs with evacuation unlikely to occur.
If failure occurs below the building and results in partial collapse	0.01 -0.1	0.05	High chance of survival. Signs of building distress should provide occupants with opportunity to take evasive action.
If failure occurs below the building and results in damage. No collapse occurs.	0.001-0.05	0.005	Very high chance of survival. Evacuation almost certain.

7. Risk Evaluation

The main objectives of risk evaluation are usually to compare the assessed risk to risk levels that are acceptable or tolerable to the community, and therefore to decide whether to accept, tolerate or treat the risks and to set

priorities for remediation. The Tolerable Risk Criteria are usually imposed by the regulator, unless agreed otherwise with the owner/client. AGS (2007d) provides discussion and gives the AGS recommendations in relation to tolerable risk for loss of life. These are summarized in the table below.

Table A7.1 AGS Suggested Tolerable loss of life individual risk.

Situation	Suggested Tolerable Loss of Life Risk for the person most at risk
Existing Slope / Existing Development	10^{-4} per annum (1E-4 pa) or 1 in 10,000 pa
New Constructed Slope / New Development / Existing Landslide	10^{-5} per annum (1E-5 pa) or 1 in 100,000 pa

It is important to distinguish between “acceptable risks” and “tolerable risks”. AGS (2007c) states that tolerable risks are risks within a range that society can live with so as to secure certain benefits. It is a range of risk regarded as non-negligible and needing to be kept under review and reduced further if practicable. Acceptable risks are risks which everyone affected is prepared to accept. Acceptable risks are usually considered to be one order of magnitude lower than the Tolerable risks.

8. References

Auckland Council (2023). ‘Guidelines on the use of AGS (2007) for landslide risk assessment in Auckland following the 2023 flooding and cyclone’. Memorandum dated 20 September 2023.

Australian Geomechanics Vol 42 No 1 March 2007 Extract “Practice Note Guidelines for Landslide Risk Management 200” AGS (2007c)

P J Finlay, G R Mostyn & R Fell (1999). ‘Landslides: Prediction of Travel Distance and Guidelines for Vulnerability of Persons’. Proc 8th. Australia New Zealand Conference on Geomechanics, Hobart. Australian Geomechanics Society, ISBN 1 86445 0029, Vol 1, pp.105-113.

Hunter. G., & Fell. R. (2002).’ Estimation of Travel Distance for Landslides in Soil Slopes’. Australian Geomechanics, Vol 37, No2.

New South Wales Government, Transport for New South Wales ‘Guide to Slope Risk Analysis’ Version 4, April 2014.

Appendix B

Glossary of Terms

DEFINITION OF TERMS

Acceptable Risk – A risk which, for the purposes of life or work, society is prepared to accept as it is with no regard to its management. Society does not generally consider expenditure in further reducing such risks justifiable.

Authority or **Council** having statutory responsibility for community activities, community safety and development approval or management of development within its defined area/region

Consequence – The outcomes or potential outcomes arising from the occurrence of a landslide expressed qualitatively or quantitatively, in terms of loss, disadvantage or gain, damage, injury or loss of life.

Creep Failure – A time-dependant deformation mechanism where constant stress is applied to a material. Creep failure can be identified by ridges the ground surface and curved tree trunks.

Dropout – A landslide feature occurring along the length of the road-side on the downslope edge. Drop outs can result in the undermining the road carriageway.

Elements at Risk – The population, buildings and engineering works, economic activities, public services utilities, infrastructure and environmental features in the area potentially affected by landslides.

Entrainment – The process of surface sediment transportation through water and mass movement.

Frequency – A measure of likelihood expressed as the number of occurrences of an event in a given time. See also Likelihood and Probability of Occurrence.

Hazard – A condition with the potential for causing an undesirable consequence. The description of landslide hazard should include the location, volume (or area), classification and velocity of the potential landslides and any resultant detached material, and the probability of their occurrence within a given period of time.

Individual Risk to Life – The risk of fatality or injury to any identifiable (named) individual who lives within the zone impacted by the landslide or who follows a particular pattern of life that might subject him or her to the consequences of the landslide.

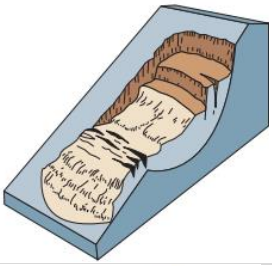
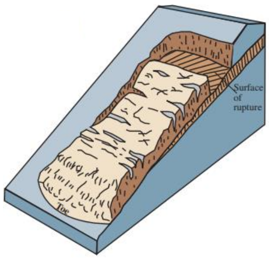
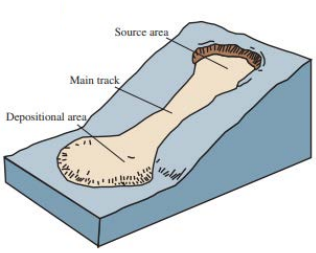
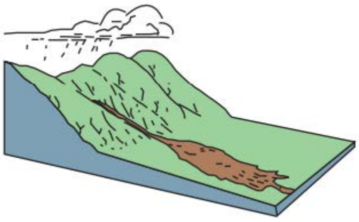
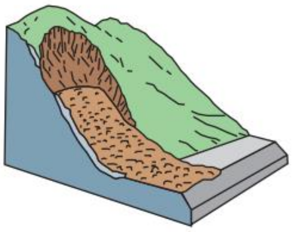
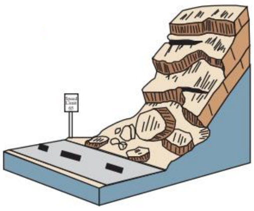
Landslide - A landslide is defined as the movement of a mass of rock, debris, or earth down a slope. The most widely used landslide classification system is that proposed by Cruden and Varnes in 1996 (after Varnes 1954 and Varnes 1978). This has been updated by Hungr, et al., 2014. In its most simple form two nouns are used to describe, firstly the type of material involved and secondly, the mechanism of failure, i.e., rock fall, debris flow.

Landslide inventory – An inventory of the location, classification, volume, activity and date of occurrence of landsliding

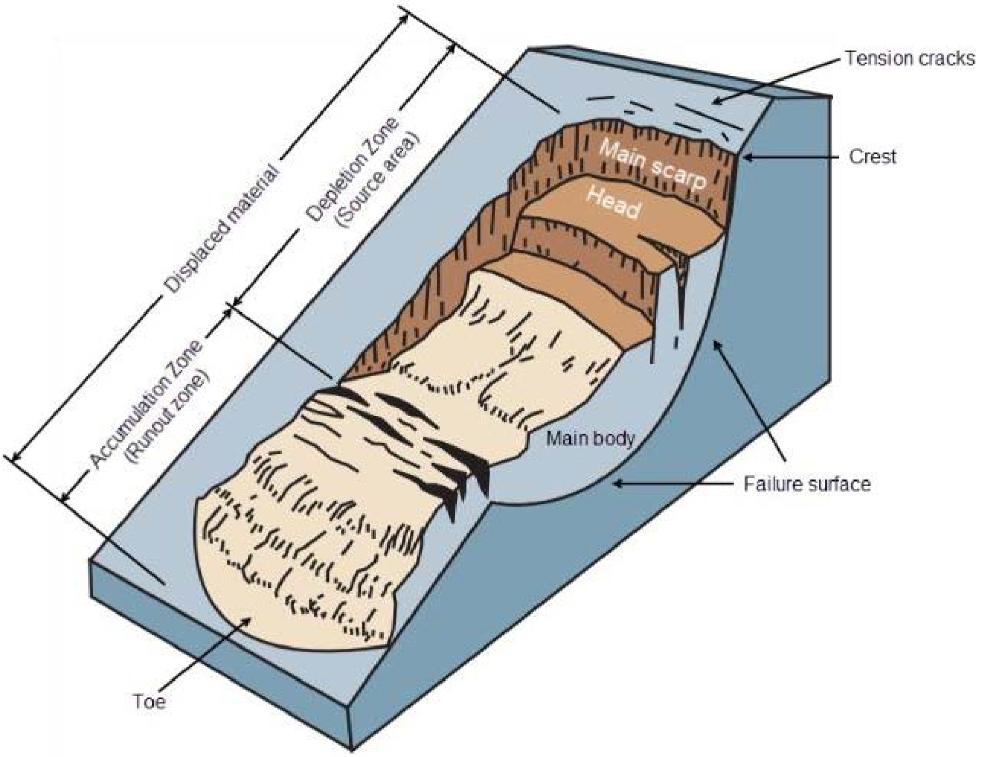
Landslide Risk - Landslide risk is defined herein as the likelihood that a particular landslide will occur and the possible consequences to a specific element at risk (property or human life) taking account of both spatial and temporal considerations.

Landslide Susceptibility – A quantitative or qualitative assessment of the classification, volume (or area) and spatial distribution of landslides which exist or potentially may occur in an area. Susceptibility may also include a description of the velocity and intensity of the existing or potential landsliding.

Landslide Classification – Referenced from Varnes, 1978.

Landslide Type	Landslide Description	Illustration
Rotational sliding	The landslide failure surface is curved concavely upward and the movement of mass is mainly rotational. Rotational movement causes back tilting of the displaced material near the headscarp.	
Translational sliding	The landslide mass moves along a planar failure surface with minor rotational movement.	
Earth flow	The movement of saturated fine-grained materials or clay bearing rocks. The displaced material forms a characteristic hourglass shape with an elongated flow path.	
Debris flow	The rapid movement of saturated, loose material caused by heavy precipitation and surface water flow. Commonly occurring on steep slopes.	
Debris avalanche	A type of debris flow that is *extremely* rapid.	
Rock fall	The separation of rocks and boulders along fractures, joints and bedding planes on steep slopes or cliffs. The movement is heavily influenced by mechanical weathering of the rock mass and gravity.	

Landslide characteristics – Modified after Varnes, 1978.



Likelihood – Used as a qualitative description of probability or frequency of the event/landslide.

Overland Flow Path – The predicated flow path of stormwater over the topography.

Permeability – The capacity of a material to allow water to pass through it. Clay materials are impermeable whereas gravels and sands are porous and therefore permeable.

Probability – A measure of the degree of certainty. This measure has a value between zero (impossibility) and 1.0 (certainty). It is an estimate of the likelihood of the magnitude of the uncertain quantity or the likelihood of the occurrence of the uncertain future event. There are two main interpretations:

(i) Statistical – frequency or fraction – The outcome of a repetitive experiment of some kind like flipping coins. It also includes the idea of population variability. Such a number is called an “objective” or relative frequentist probability because it exists in the real world and is in principle measurable by doing the experiment.
(ii) Subjective probability (degree of belief) – Quantified measure of belief, judgement, or confidence in the likelihood of a outcome, obtained by considering all available information honestly, fairly and with a minimum of bias. Subjective probability is affected by the state of understanding of a process, judgement regarding an evaluation or the quality and quantity of information. It may change over time as the state of knowledge changes.

Probability of Occurrence – used interchangeably with Likelihood.

Quantitative Risk Analysis – an analysis based on numerical values of the probability, vulnerability and consequences, and resulting in a numerical value of the risk.

Recurrence Interval (repeat period) – An estimated value of how often an event occurs based on the average time between passed events.

Regression – The continual movement of a landslide downslope and or widening/retreat of the headscarp.

The **Regulator** will be the responsible body/authority for setting Acceptable/Tolerable Risk Criteria to be adopted for the community/region/activity, which will be the basis for setting levels for Acceptable and Tolerable Risk in the application of the risk assessment guidelines.

Risk – A measure of the probability and severity of an adverse effect to health, property or the environment. Risk is often estimated by the product of probability x consequences. However, a more general interpretation of risk involves a comparison of the probability and consequences in a non-product form.

Risk Analysis – The use of available information to estimate the risk to individuals, population, property or the environment from hazards. Risk analyses generally contain the following steps: scope definition, hazard identification and risk estimation.

Risk Assessment – The process of risk analysis and risk evaluation.

Risk Control or Risk Treatment – The process of decision making for managing risk and the implementation or enforcement of risk mitigation measures and the re-evaluation of its effectiveness from time to time, using the results of risk assessment as one input.

Risk Estimation – The process used to produce a measure of the level of health, property or environmental risks being analysed. Risk estimation contains the following steps: frequency analysis, consequence analysis and their integration.

Risk Evaluation – The stage at which values and judgements enter the decision process, explicitly or implicitly, by including consideration of the importance of the estimated risks and the associated social, environmental, and economic consequences, in order to identify a range of alternatives for managing the risks.

Risk Management – The complete process of risk assessment and risk control (*or risk treatment*).

Runout Distance – The horizontal distance from the source area to the distal toe.

Susceptibility – see Landslide Susceptibility

Temporal-Spatial Probability – The probability that the element at risk is in the affected area at the time of the landslide.

Tolerable Risk – A risk within a range that society can live with so as to secure certain net benefits. It is a range of risk regarded as non-negligible and needing to be kept under review and reduced further if possible.

Transgression-regression cycles – Sedimentary deposits formed from cycles of sea level rise and fall.

Travel Angle – The angle from the crest of the source area to the distal toe of the debris (run out zone)

Vulnerability – The degree of loss to a given element or set of elements within the area affected by the landslide hazard. It is expressed on a scale of 0 (no loss) to 1 (total loss). For property, the loss will be the value of the damage relative to the value of the property; for persons, it will be the probability that a particular life (the element at risk) will be lost, given the person(s) is affected by the landslide.

ghd.com

→ The Power of Commitment

Appendix E-3

87 Domain Crescent Landslide Risk Assessment

Waitākere Coastal Communities Landslide Risk Assessment

87 Domain Crescent, Muriwai

Auckland Council

28 March 2024

→ **The Power of Commitment**

Project name	AC Geo Panel - Waitākere Coastal Communities LHRA
Document title	Waitākere Coastal Communities Landslide Risk Assessment | 87 Domain Crescent, Muriwai
Project number	12612462
File name	12612462- RiskAssess87 Domain MuriwaiFINALR1.docx

Status Code	**Revision**	**Author**	**Reviewer**		**Approved for issue**		
			Name	**Signature**	**Name**	**Signature**	**Date**
S4	1	Ryan Hayes	Don Macfarlane	D Macfarlane	Roy Pearson	Roy Pearson	28/03/2024
[Status code]							
[Status code]							
[Status code]							

GHD Limited
GHD
27 Napier Street, GHD Centre Level 3
Freemans Bay, Auckland 1010, New Zealand
T +64 9 370 8000 | **F** +64 9 370 8001 | **E** aklmail@ghd.com | **ghd.com**

Contents

Table index

Figure index

Appendices

1. Introduction

1.1 Background

Two significant rainfall events affected the Waitakere area in late January and early February, resulting from the impacts of ex-tropical cyclones Hale and Gabrielle, respectively.

The Cyclone Gabrielle weather event of 14 February 2023 resulted in widespread catastrophic flooding and slope instability in the settlement of Muriwai where several debris avalanches (which included rocks and trees) occurred, some of which turned into saturated debris flows as they travelled downslope. These flows resulted in damage to buildings and infrastructure. Two fatalities occurred due to impact of landslides on private dwellings. This tragic event was similar to a 1965 storm event that also claimed two lives.

Following the February event, rapid building assessment of residential properties was undertaken in Muriwai, with some houses having access by owners restricted (a yellow placard – e.g. access in daylight hours only) and some for which no access was permitted (a red placard).

GHD has been engaged by Auckland Council (AC)[1] to carry out landslide risk assessments and to provide associated landslide risk management advice and geotechnical investigations recommendations in the Waitakere area, specifically for the residential areas of Muriwai, Piha and Karekare. These assessments were necessary due to widespread, damaging landslides associated with Cyclone Gabrielle in February 2023. GHD has completed a landslide risk assessment[2], whereby some properties were identified as having an unacceptably high risk of being impacted by future large landslides.

1.2 Purpose of this report

The residential property at 87 Domain Crescent, Muriwai ('the site') has been assessed by GHD as having an acceptable risk from large scale landslides[3] (see the November 2023 report). However, a localised, damaging landslide has occurred near the property, and the purpose of this assessment is to carry out a Quantitative Landslide Risk Assessment (QRA) to estimate the risk of Loss of Life to individuals at the property. The outcome of the QRA will be used to inform subsequent property risk categorisation and building placard designation review by AC.

1.3 Scope

The scope of work requested by AC was as follows:

- Review available historical and recent imagery including LiDAR.
- Review pertinent historical data and GHD work undertaken as part of the wider Muriwai landslide risk assessment reported in GHD (November 2023).
- Undertake a site engineering geological assessment of landslide hazards relevant to the property.
- Undertake a QRA where landslide hazards have been identified that pose a Loss of Life landslide risk using the Australian Geomechanics Society Practice Note Guidelines for Landslide Risk Management, commonly known as AGS (2007c).
- Deliver report(s) documenting the QRA inputs and outcome.

Specifically excluded are an assessment of property risk, site specific subsurface geotechnical investigations, service inspections, and groundwater monitoring.

This assessment considers geotechnical matters only. There may be other non-geotechnical considerations that affect the final property risk categorisation or placard designation of which GHD are not aware, such as flood risk and structural damage to property.

---

[1] Under Contract CW198379, Master Services Agreement CCCS: CW74240 dated 7/09/2019

[2] Dated 03/11/2023, document file ref 12612462_Overall Report FINALRev0.docx

[3] In the GHD November 2023 report, 'large scale' landslide hazards refers to landslides originating from the main escarpment that typically have a volume of more than about 50 m3 with the potential to cause total or partial collapse of a dwelling.

Identification of options for the mitigation of geotechnical hazards has not been undertaken as part of this study.

Although considered unlikely, GHD reserves the right to amend the opinions, conclusions and recommendations provided within this report, should additional geotechnical information become available.

1.4 Our Approach

GHD have completed a landslide risk assessment for Muriwai that assessed the risk to life of large-scale landslide hazards to inform possible future dwelling hazard designations. The assessment was limited to ‘large scale’ landslide hazards originating from the main escarpment located to the south-east of Muriwai because the initial placard assessment was largely aimed at mitigating risks associated with these.

Smaller, more localised landslide hazards that could originate (or may have already initiated) from other areas in Muriwai such as within the footprint of individual residential properties were not considered in the overall risk assessment. However, these have the potential to cause damage to dwellings and subsequently pose a risk to life for residents, partly due to the relatively steep topography and the potential for high travel velocity.

The approach of identifying landslide hazards over large and common source areas, such as that used for the November 2023 Muriwai assessment, does not capture numerous, smaller scale, localised landslides. For this reason, a QRA is presented for the site based on an assessment that includes site observations and a review of the GHD (2023) report.

The QRA undertaken for this report only assesses risk to life to occupants of the dwelling due to landsliding. The assessment considers a number of hazard scenarios as follows:

1. the **most likely significant landslide hazard** based on the observed hazards with respect to the mapped landslides and their distribution within the broader landscape. In addition, considerations of the hazard relationship to topography, position on the hillslope and proximity to the elements at risk are also included. This represents a credible hazard scenario following a triggering event with a similar frequency as the February 2023 event.
2. Existing geohazards that have resulted from recent failures with the potential to pose risk to life, such as regression and/or remobilisation of translational failures that are upslope or downslope of a dwelling, or failure of oversteepened fill and cut slopes. These represent hazards that exist at the site and may be triggered by a more frequent event in the range of *certain to almost certain*[4] to occur.
3. Other possible geotechnical slope instability hazards that have the potential to pose a risk to life, such as failures of fills, cuttings and failed retaining walls. These represent hazards that may have a range of likelihood from *almost certain to possible*.

The process of risk assessment involves estimation of likelihood, consequence and risks based on available information for the study site. The methodology used for the QRA is outlined in Appendix A. The site-specific input parameters and uncertainties are described in Section 3.

A glossary of terminology is presented in Appendix B.

---

[4] The terminology used when referencing probabilities has been adopted from the Qualitative Measures of Likelihood table for assessing risk to property in AGS (2007c). For this assessment, these terms and associated probabilities are Certain = 0.99, Almost Certain = 0.1, Likely = 0.01, Possible = 0.001, Unlikely = 0.0001, Very Unlikely = >0.00001

2. Site conditions

2.1 Site description

The site is located at 87 Domain Crescent, Muriwai, legally described as Lot 63 DP 39644 and it has an approximate area of 827 m^2. As shown in Figure 2.1, the property is located on Domain Crescent on the lower portion of the approximately 80 m high main escarpment that is aligned to the northeast and separates the township between lower-lying plateaus to the west (near sea level), and higher areas to the south and east. Locally, the escarpment extends from Domain Crescent at its base (at an elevation of approximately 60 m RL), to Oaia Road at its crest (at an elevation of approximately 150 m RL).

There is a single dwelling on the property located towards the base of the slope, adjacent to Domain Crescent. The dwelling is constructed on timber poles built into the slope which has been modified slightly to accommodate it. The natural, vegetated slope behind the dwelling (Figure 2.1 and Figure 2.2) has an average slope gradient of approximately 35° which increases to approximately 60° where it meets a prominent north-trending ridgeline at the eastern extent of the property boundary.

Two 'large' landslides originating at an elevation of approximately 110 m above the site occurred during Cyclone Gabrielle but did not affect the dwelling. A third, smaller scale, localised failure originating within the neighbouring property (No. 85) that partly encroaches within the property boundary of No.87 (mapped on Figure 2.3) at approx. 83 m RL developed into a debris flow which travelled in a southwest direction impacting the rear of the neighbours dwelling (No. 85) causing structural damage.

Two overland flow paths are mapped from Auckland Council's GeoMaps to the north and south of the property boundary (Figure 2.3) originating at approximately 105 m RL and 75 m RL to the southeast of the dwelling. Both overland flow paths have a catchment size of approximately 2000 m^2 to 4000 m^2. The travel paths of the debris associated with the two large scale landslides above the site, to the north and south, appear to correlate with the mapped overland flow paths. No overland flow paths are mapped on the slopes within the property boundary.

Figure 2.1 Steep vegetated slope at the rear of the dwelling

Figure 2.2 Steep vegetated slope at the rear of the dwelling

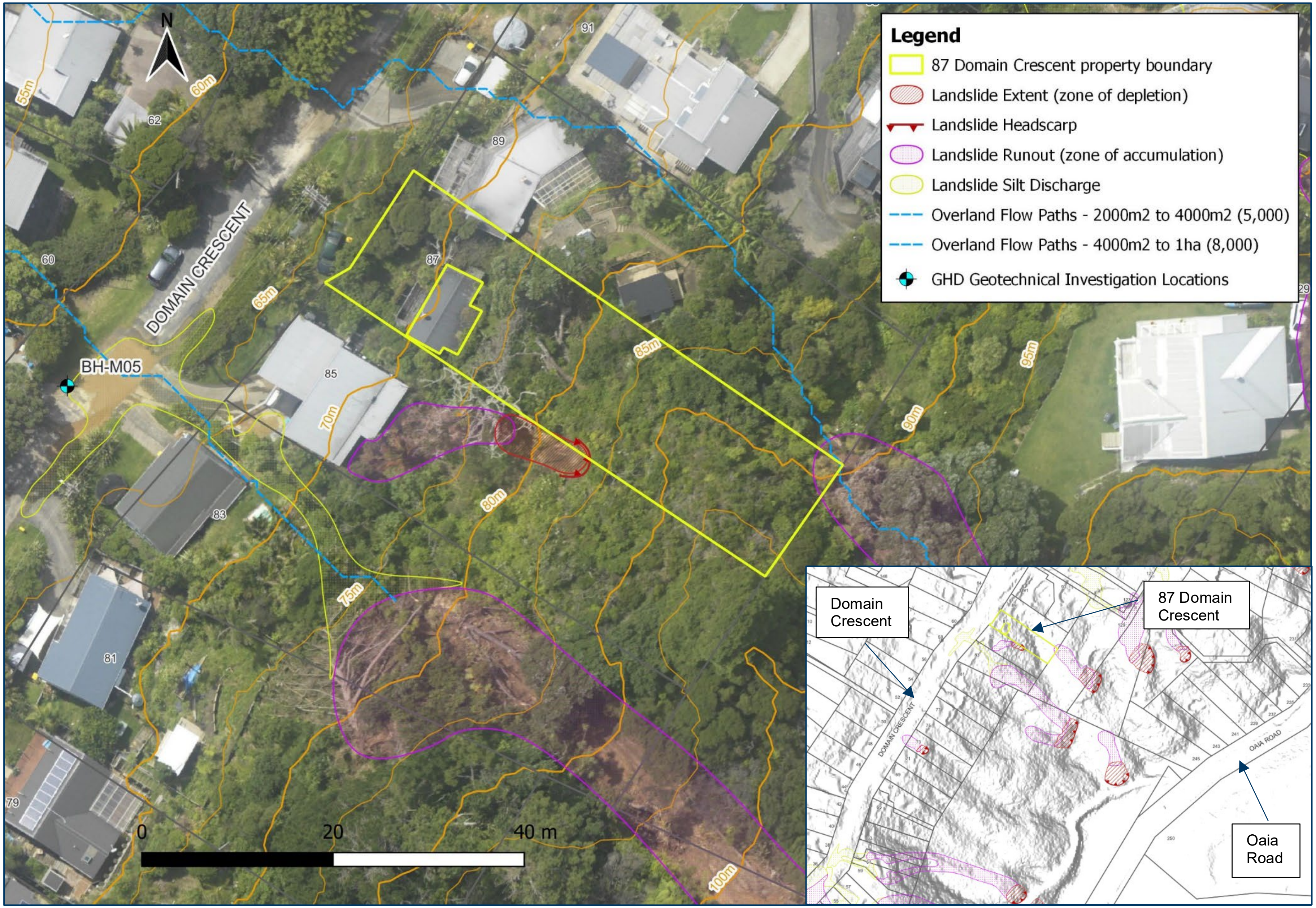


Figure 2.3 *Site location along Domain Crescent*

2.2 Published geology

The published 1:50,000 scale geological map of the area (Hayward, 1983) indicates the site is entirely underlain by the Awhitu Sand Formation (mp), part of the Kaihu Group (Figure 2.4).

Awhitu Sands (‘qs’) are Pliocene aged (less than 2 Mya) characterised as ‘coarse sand, clayey, often limonitised (as laterally discontinuous layers), with minor tuff, lignite and siltstone’ (Hayward, 1983). The formation originated as coastal sand deposits. Awhitu Sands are generally oxidised to an orange-brown colour when exposed at the surface, resulting in a weak iron-cementation that allows for the development of large, more than 50 m high steep slopes, such as the escarpment.

The formation is weakly bedded and cross-bedded at the sub metre scale. Locally the formation is inferred to dip north and eastward at a shallow angle. Occurrences of silty/clayey horizons are occasionally visible in outcrop and have been encountered within boreholes, however it is unclear how persistent they are spatially.

Although not mapped, more recent colluvium material formed as a result of ongoing erosion and periodic landsliding associated with escarpment recession is likely present on the basal/lower slopes of the escarpment.

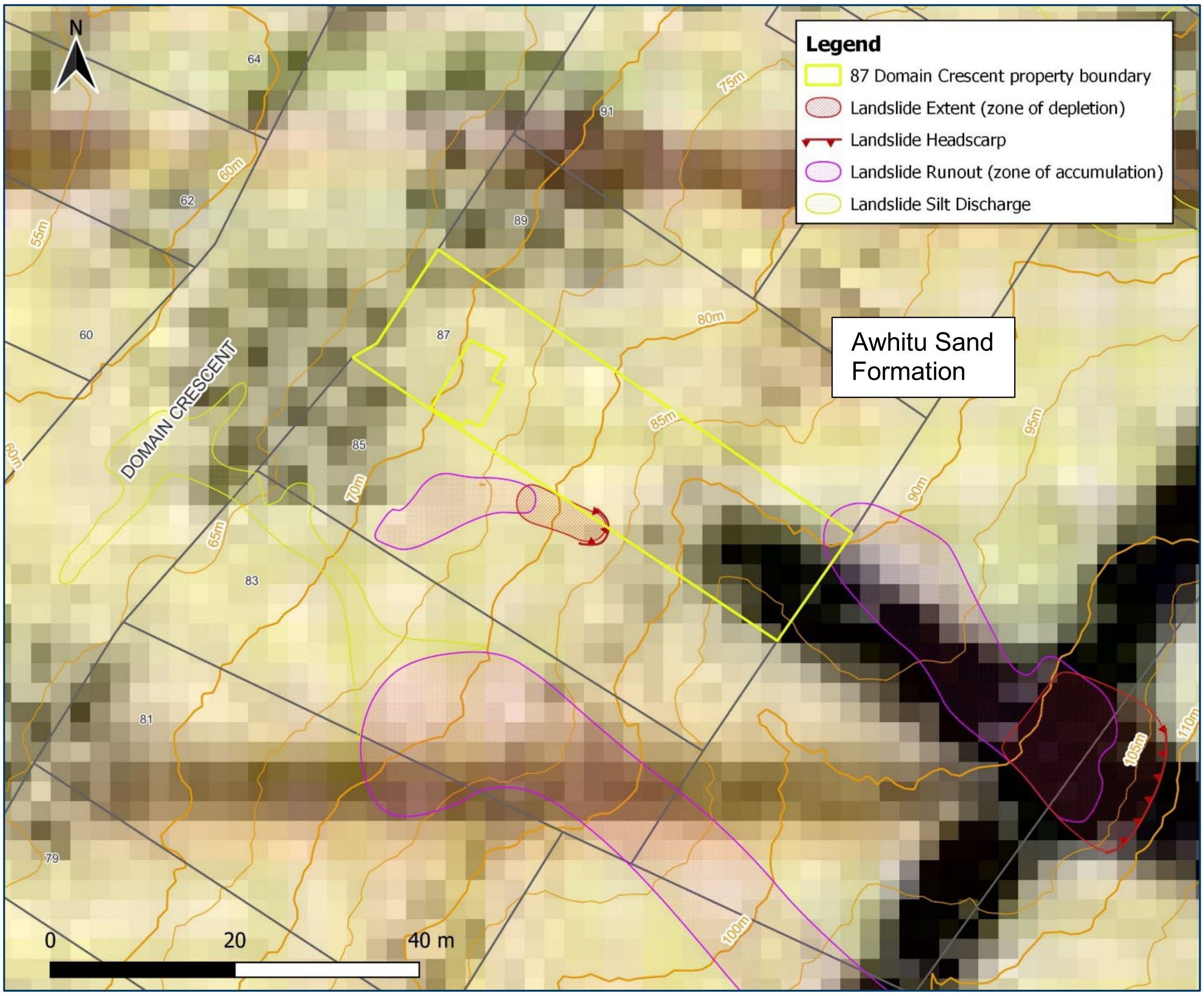


Figure 2.4 *Excerpt of the Waitākere 1:50,000 scale geological map (Hayward, 1983[5]), illustrating the underlying geology at the site location.*

---

[5] Hayward, B.W. 1983: Sheet Q11, Waitakere. Geological Map of New Zealand 1:50,000 Map

2.3 Historical data summary

A summary of the historical data relevant to 87 Domain Crescent is presented in Table 2.1.

Table 2.1 Summary of historical data

	Applicable data available	Notes
Historic aerial photos	1940, 1950, 1953, 1975, 2000, 2004, 2008, 2010-2011, 2015-2017, 2022	- No obvious evidence of instability was identified from the historical aerials within the property itself. - Evidence of wider scale erosion evident from 1940, where many of the spurs leading off main escarpment are bare as well as section of the crest of the escarpment. Suggests ongoing erosion of surficial soil. No regression of escarpment observed. - Photos sourced from Retrolens and Auckland Council Geomaps.
NZ Geotechnical database	One borehole (BH-MH05, Figure 2.1) completed by GHD in August 2023. Located 30 m west of south-west corner of property boundary.	- 10.95 m deep borehole. - 0 – 5.6 m: Ancient colluvial deposits generally comprising sandy silt and silty sand. - 5.6 – 10.95 m: Awhitu sand formation comprising variably cemented sand (medium dense to very dense)
Council GeoMaps	Overland flow data from Auckland City Council ArcGIS.	- Discussed in Section 2.1.
Rapid building Assessment Geotech reporting	N/A	N/A
Independent geotechnical reports	N/A	N/A
Anecdotal information	N/A	N/A
LiDAR Imagery	Feb 2023 Digital Terrain Model.	- Headscarps in the escarpment crest suggest ongoing recession through debris flows. - Headscarps also seen on smaller ridgelines extending down the escarpment. However no clear evidence of these in the ridgeline within the property. - Possible hummocky ground on the natural slopes above the dwelling leading up to the ridgeline on 87 Domain Crescent.

2.4 Engineering geological model

2.4.1 Awhitu Sand Formation

Awhitu Sands are exposed within the entire escarpment and have generally been described as medium dense to very dense sands overlying massive, extremely weak, moderately weathered, iron-cemented fine to coarse sandstone. Irregular layers of clay and silt rich material are typically spaced every 5-10 m and relatively thin (less than 1.0 m and often less than 0.1 m). The strength profile of the Awhitu Sands displays a relatively linear increase with depth.

The in-situ nature of the Awhitu Sands suggests they are relatively permeable. However, as discussed in the November report there is also significant evidence for perched groundwater tables shown by:

- Multiple occurrences of groundwater seeps or springs emerging within the middle and base of the escarpment slope face, from above underlying (presumed aquiclude) layers of clay and silt rich beds as well as heavily oxidised iron pans
- Variable and sharply changing weathering profile with localised layers of cemented iron oxidised sand between un-oxidised material at depth.

2.4.2 General landslide characteristics

As described in the November report (GHD 2023), the landslides identified across Muriwai following the February 2023 event can be categorised into two types based on their physical characteristics as follows:

Large slips: typical headscarp widths of 30-70 m, with source and debris runout areas more than 100 m in length, often extending well past the base of the escarpment onto the flatter slopes below, and

Smaller isolated slips: generally with headscarp widths of less than 30 m and extending less than 50 m. As a result debris from these landslides generally did not reach the base of the escarpment.

2.4.3 Landslide affecting the site

The landslide that occurred above the site, within the neighbour's property, is illustrated by site mapping on Figure 2.5 and is also shown in the context of LiDAR Hillshade imagery on Figure 2.6 below. An interpretive cross section prepared through the site is presented in Figure 2.7. Ground conditions have been interpreted from a combination of historical data, site mapping and nearby geotechnical investigation data. The cross section is indicative only and may not be representative of actual conditions.

The landslide headscarp (Figure 2.8) has an approximate width of 7 m and is approximately 10 m above the rear of the dwelling, close to the crest of a ridgeline. Following a high degree of ground saturation, the landslide initiated on a 30-35° vegetated slope as a shallow (~ 0.5 m deep) translational failure (Figure 2.9) which developed into a debris flow, entraining additional material on its descent. The initial landslide source volume was approximately 20 m^3, increasing to approximately 60-80 m^3 following entrainment. The landslide impacted the rear of the neighbouring dwelling (Figure 2.10). No landslide debris entered the property of No. 87.

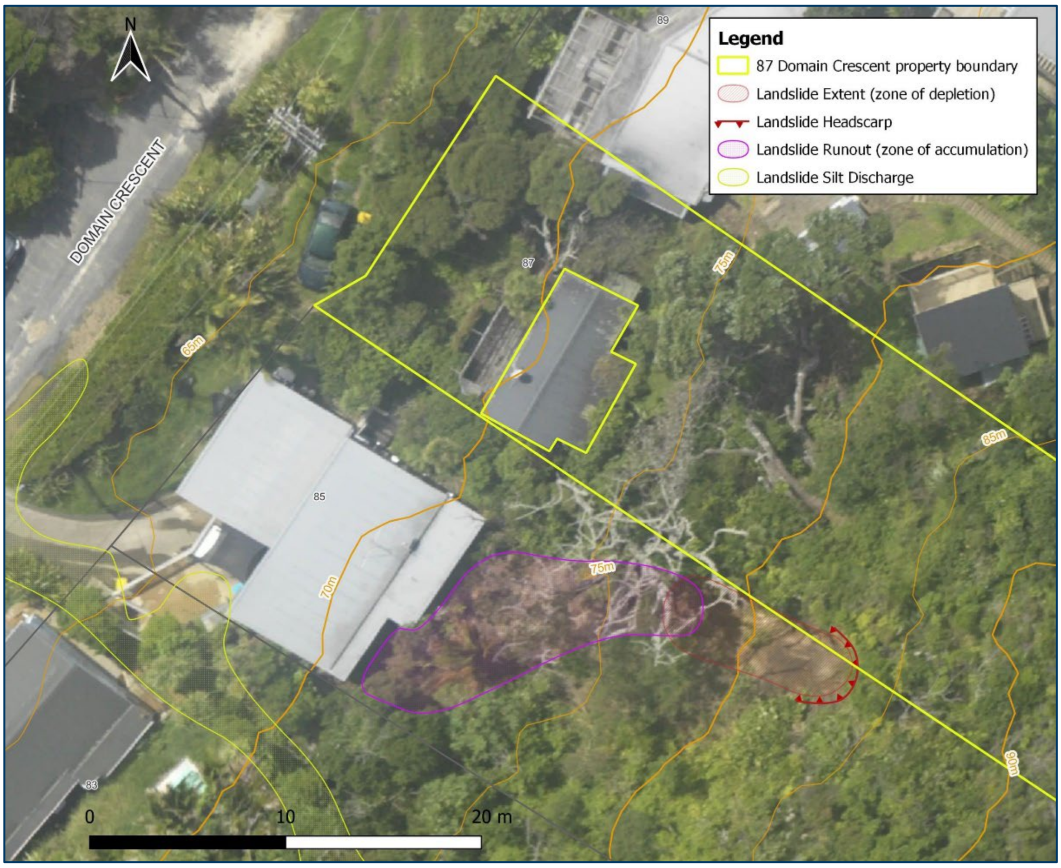


Figure 2.5 *GHD site mapping of the landslide affecting the site*

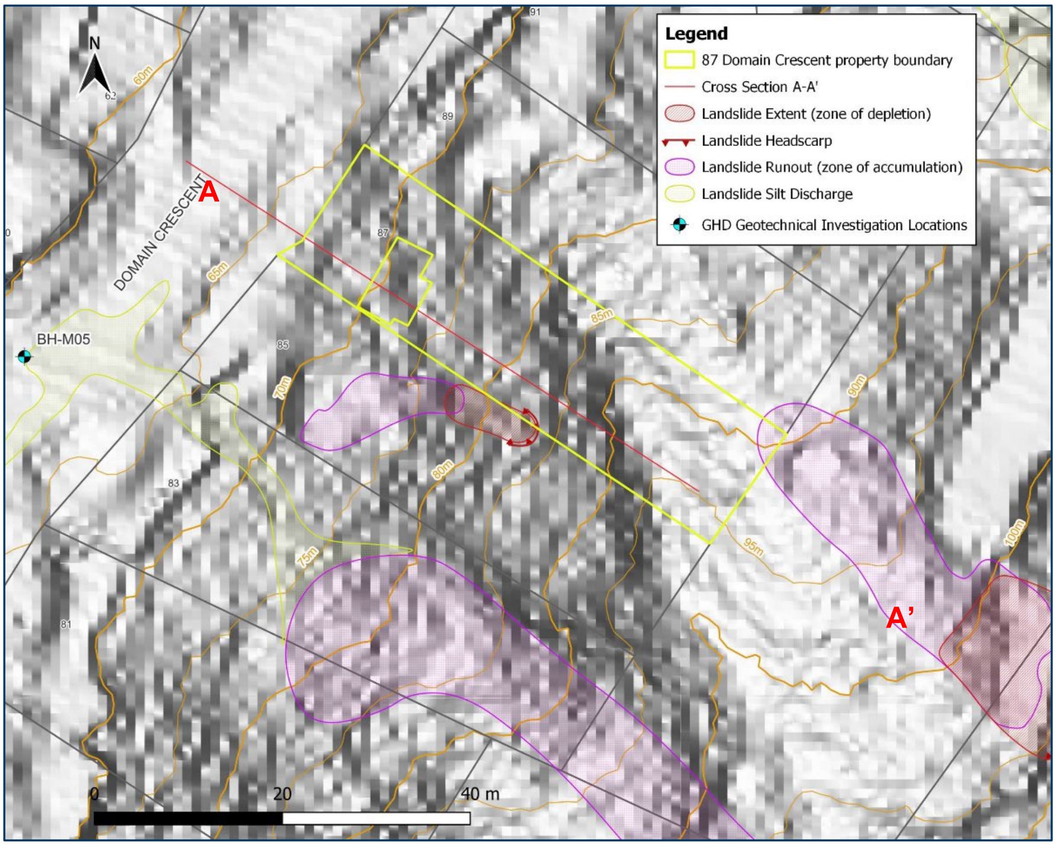


Figure 2.6 *Landslide location relative to the site shown on LiDAR Hillshade (source: Auckland Council Feb 2023).*

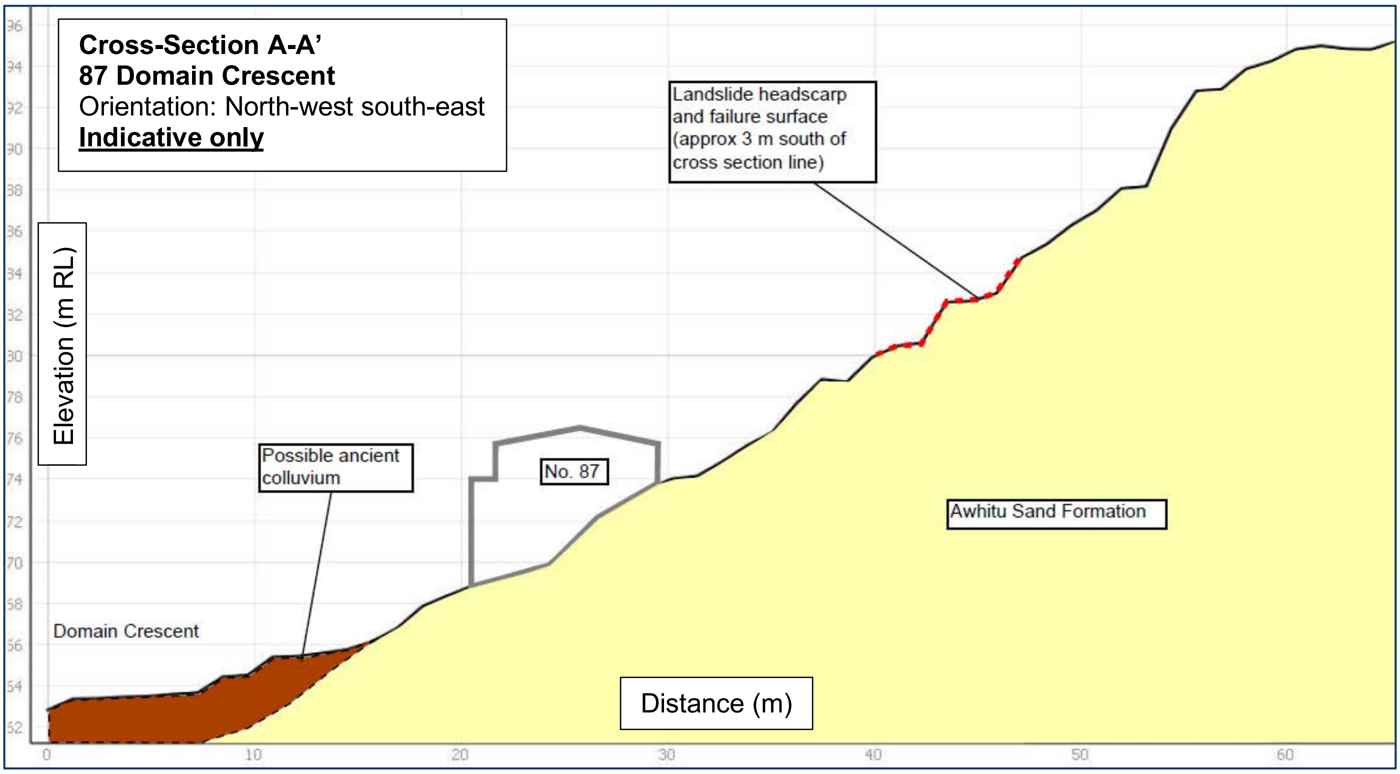


Figure 2.7 Indicative cross section A-A' through 87 Domain Crescent

Figure 2.8 Exposed headscarp of landslide.

Figure 2.9 Failure surface (evacuated zone) exhibiting evidence of post failure erosion. Looking upslope.

Figure 2.10 Debris piled up at the rear of the dwelling at No. 85 Domain Crescent (estimated up to 1.5 m thick)

3. Landslide risk estimation

The Australian Geomechanics Society Landslide Risk Management guidelines, published in 2007 and now commonly referred to as AGS (2007), have been adopted for the following unmitigated loss of life landslide risk assessment. Appendix A provides background information and guidance on how the methodology has been applied for assessing risk to life at the site.

The existing dwelling has been considered as the element at risk for this assessment. Where appropriate, sensitivity checks have been undertaken for comparative purposes.

3.1 Hazard characterisation

The landslide hazard considered as part of this assessment is as follows:

- **LS1** (Landslide Hazard 1) – The most likely future landslide to occur somewhere on the slopes above the property. The landslide would be a shallow failure with a volume in the order of 20-40 m^3 that develops into a debris flow entraining additional downslope material. The assumed landslide characteristics have been inferred from observations of the previous failure and landslides to occur elsewhere in Muriwai. The possible source area considered for a future landslide above the dwelling, highlighted on Figure 3.1 and Figure 3.2 below, is constrained by two relatively prominent ridgelines.

3.2 Likelihood of landsliding ($P_{(H)}$)

The basis for estimating probability of occurrence for the landslide hazard considered as part of this assessment is provided in Appendix A and the probabilities adopted are provided below.

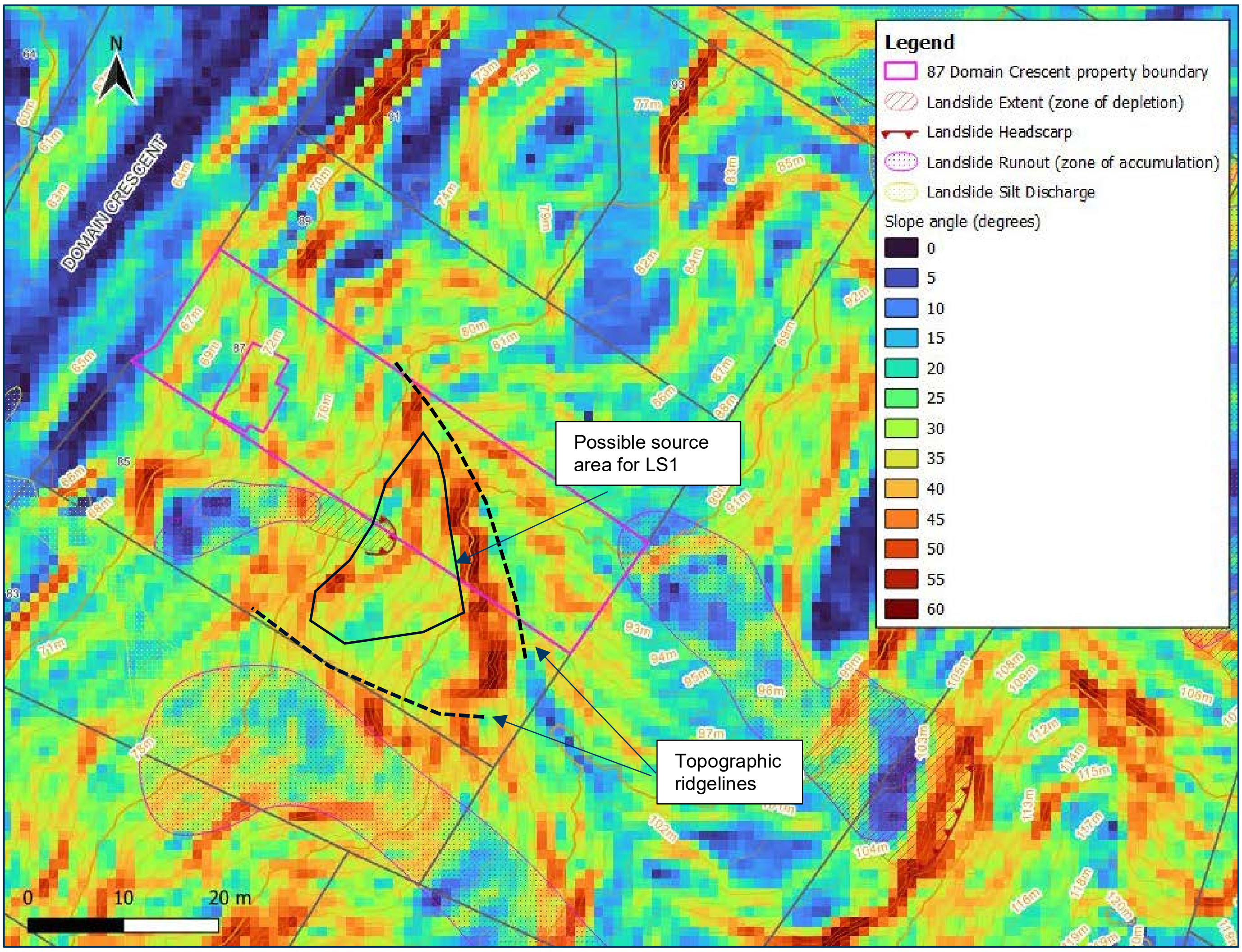
3.2.1 Likelihood of LS1

Two considerations of probability for occurrence for the most likely future landslide are:

- $P_{(H'1)}$ is the probability that the rainfall threshold for the most likely significant landslide is exceeded, which is taken as a proxy for landslide initiation. This is assumed to be 1 in 100 or **0.01** (see analysis by AC in Appendix A) or 1 in 50 or **0.02** under the influence of future climate change.
- $P_{(H'2)}$ is the probability that the slope above the dwellings fails. A single landslide occurred on the slopes above and near the dwelling. Considering the total area of the slope above the dwelling with similar conditions, and therefore considered susceptible to failure, an estimate of 5% failed during the February 2023 rainfall event. A value of $P_{(H'2)}$ **= 0.05** has been adopted.

3.3 Probability of spatial impact ($P_{(S:H)}$)

Our estimate of spatial probability is based on several factors which depend on the landslide hazards being considered and site-specific slope conditions. Our approach is detailed in Appendix A. Figure 3.1 and Figure 3.2 below provide an indication of the slope conditions at 87 Domain Crescent and the surrounding area (slope angles and inferred preferential flow paths, respectively).



Possible source area for LS1

Topographic ridgelines

Figure 3.1 Slope map of 87 Domain Crescent and surrounding area. Slope angles based on 2023 DTM data.

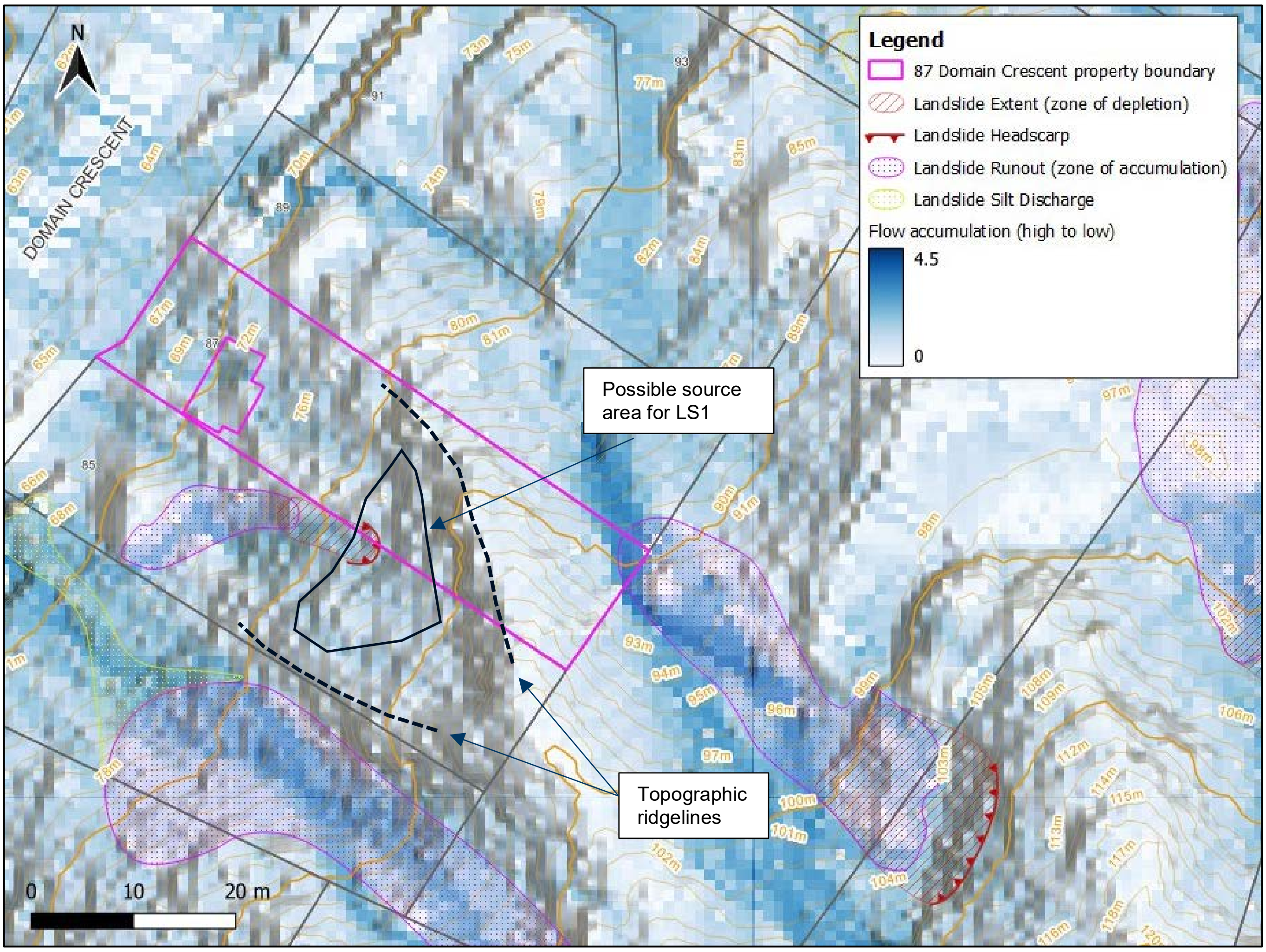


Figure 3.2 *Flow accumulation map of 87 Domain Crescent and surrounding area. Indicates preferential flow path for surface water. Modelling based on 2023 DTM data.*

3.3.1 Probability of spatial impact (LS1)

Two conditional factors are considered for the most likely significant landslide:

- $P_{(S':H'1)}$ is the probability that if the landslide occurs it travels in the direction of the site. Based on the position of the dwelling at the base of a relatively planar slope exhibiting a somewhat concave geomorphology at its crest, a landslide initiating in the possible source area above the site (Figure 3.1) would likely travel downslope (northwest) towards the dwelling. Based on the flow accumulation plot (Figure 3.2) and the topographic contours shown in Figure 2.3, we judge that a landslide is unlikely to take a preferential flow path which diverts it away from the dwelling. A value of **1.0** is adopted.
- $P_{(S':H'2)}$ is the probability that if the landslide occurs it will reach the dwelling. The natural slopes above are generally steep (~35°). Based on the landslide volume approach (using an approximate landslide volume of 50 m^3), a travel angle of 35° would be adopted (Appendix A methodology based on data from Piha and Karekare). This would project the landslide to the rear of the dwelling.

  Empirical methods in the GHD (2023) Muriwai risk assessment report indicate that, based on a downslope angle approach (using approximately 35°), the predicted travel distance angle would be approximately 30° (for an unconfined travel path). This value also generally agrees with published data in Hunter & Fell (2002) (approximately 32°). This would project the landslide beyond the dwelling. Therefore, a probability of impact value of **1.0** has been adopted as a conservative approach.

3.4 Temporal spatial probability ($P_{(T:S)}$)

As discussed in Appendix A, a temporal spatial probability of **0.68** is the adopted value for each property and has been used in this assessment.

3.5 Vulnerability ($V_{(D:T)}$)

In the event a debris flow reaches the dwelling from the slopes above, it is likely to be small[6] in size and have a flow depth in the order of 1.0 m. Given the landslide is likely to initiate at similar elevation to the previous landslide to occur on the neighbouring property, it is assumed it will have a similar behaviour, impacting the rear of the dwelling resulting in significant structural damage and potential collapse. A value of **0.8** is adopted for LS1.

3.6 Unmitigated Risk Estimation

A summary of the risk estimation for each conceivable landslide hazard is presented in Table 3.1 below. A sensitivity check assuming a higher probability of occurrence for $P_{(H)}$ is included for comparative purposes.

Table 3.1 Summary of unmitigated risk estimation for each hazard type by domain.

Hazard	**Annual probability of the landslide** $P_{(H)} = P_{(H'1)} \text{ x } P_{(H'2)}$	**Spatial probability** $P_{(S:H)} = P_{s':H'1)} \text{ x } P_{(S':H'2)}$	**Temporal probability** $P_{(T:S)}$	**Vulnerability** $V_{(D:T)}$	**Risk** $R_{(LOL)}$	**Risk evaluation***
LS1 ***(most likely future landslide hazard)***	**0.01 x 0.05**	**1.0 x 1.0**	**0.68**	**0.8**	**$2.7 \text{ x } 10^{-4}$**	**Not tolerable**
LS1 *Sensitivity check*	*0.02 x 0.05*	*1.0 x 1.0*	*0.68*	*0.8*	*$5.4 \text{ x } 10^{-4}$*	*Not tolerable*

**The evaluation is a guide only based on recommendations from AGS (2007) which provides a suggested tolerable Loss of Life Risk for the person most at risk.*

We acknowledge that assessing risk has an inherent degree of uncertainty and may only be accurate to within half an order of magnitude. This level of uncertainty would not change the outcome of the analysis. Refer to Appendix A for further discussion.

---

[6] Table A3.1 Landslide size classification in Appendix A

4. Mitigation option

4.1 General

A mitigation measure has been selected that could be adopted at this site to lower the risk level associated with future landslides (LS1) occurring above the site to a tolerable level. The following section provides a high-level conceptual mitigation option for the dwelling with an estimated cost using the principles used by GHD for other properties in Muriwai[7].

Landslide hazard 1 (LS1) is considered as the hazard requiring mitigation and for the purpose of this assessment it is assumed that the landslide would occur on the slopes directly above the dwelling, have a maximum volume of approximately 40 m^3 and an estimated velocity of rapid to very rapid[8].

The selection is based on existing information and site knowledge. Some of the considerations when selecting a suitable mitigation option include:

- The slope angle and foundation conditions of the proposed barrier location. This is an important consideration for mass gravity embankment-type barriers.
- Site conditions that may enable or limit access for construction.
- The location of the property boundary, with the aim of locating the mitigation structure within this.
- The volume capacity of the proposed debris flow barrier.
- The barrier will require ongoing inspection and maintenance, which is a future liability for the owner.
- The barrier will require access to enable removal of debris.
- The locations and limitations associated with the presence of trees needs to be considered in the design and construction of barriers.
- Whether the site is within a Significant Ecological Area (SEA) where modification of the environment may trigger Resource Consent requirements.

4.2 Selected mitigation option

A flexible debris flow ‘fence type’ barrier has been selected as the most feasible option to mitigate the risk to the dwelling on the site. The limited access at the rear of the property and the steep slope conditions preclude alternative options such as a mass gravity embankment-type barrier. As shown in Figure 4.1 below, the flexible barrier comprises mesh supported by steel posts with upslope and lateral wire support ropes that are anchored several metres into the ground. An example of a commercially available proprietary system that could be adopted is a Geobrugg SL150 (3.5 m constructed height) or a modified RXI300 (5 m constructed height) or equivalent.

---

[7] Reported in GHD report, dated 12 October 2023 ‘Muriwai debris flow mitigation’, reference 12612462_MitigationOptionsMuriwai final draft

[8] Cruden, D., & Varnes, D. (1996). Landslide types and processes. In K. Turner & R. Schuster (Eds.), Landslides: Investigation and Mitigation (Chap. 3, pp. 36–75). Transportation Research Board: Washington.

Figure 4.1 Example of proprietary flexible debris flow barrier

Elements of the barrier system may be exchanged to accommodate specific site conditions. An example of this is where an end terminal is located close to a property boundary. Wire ropes attached to the top of the barrier end post attach to ground anchors several metres upslope and laterally. A pressure post can replace this end post to keep hardware within the property (see Figure 4.2).

The proposed barrier location is above the dwelling at an approximate elevation of 76 m RL and has an approximate length of 10 m (Figure 4.3 below).

Figure 4.2 Example of a pressure post that can be used at the end of flexible barriers that may be used at property boundaries

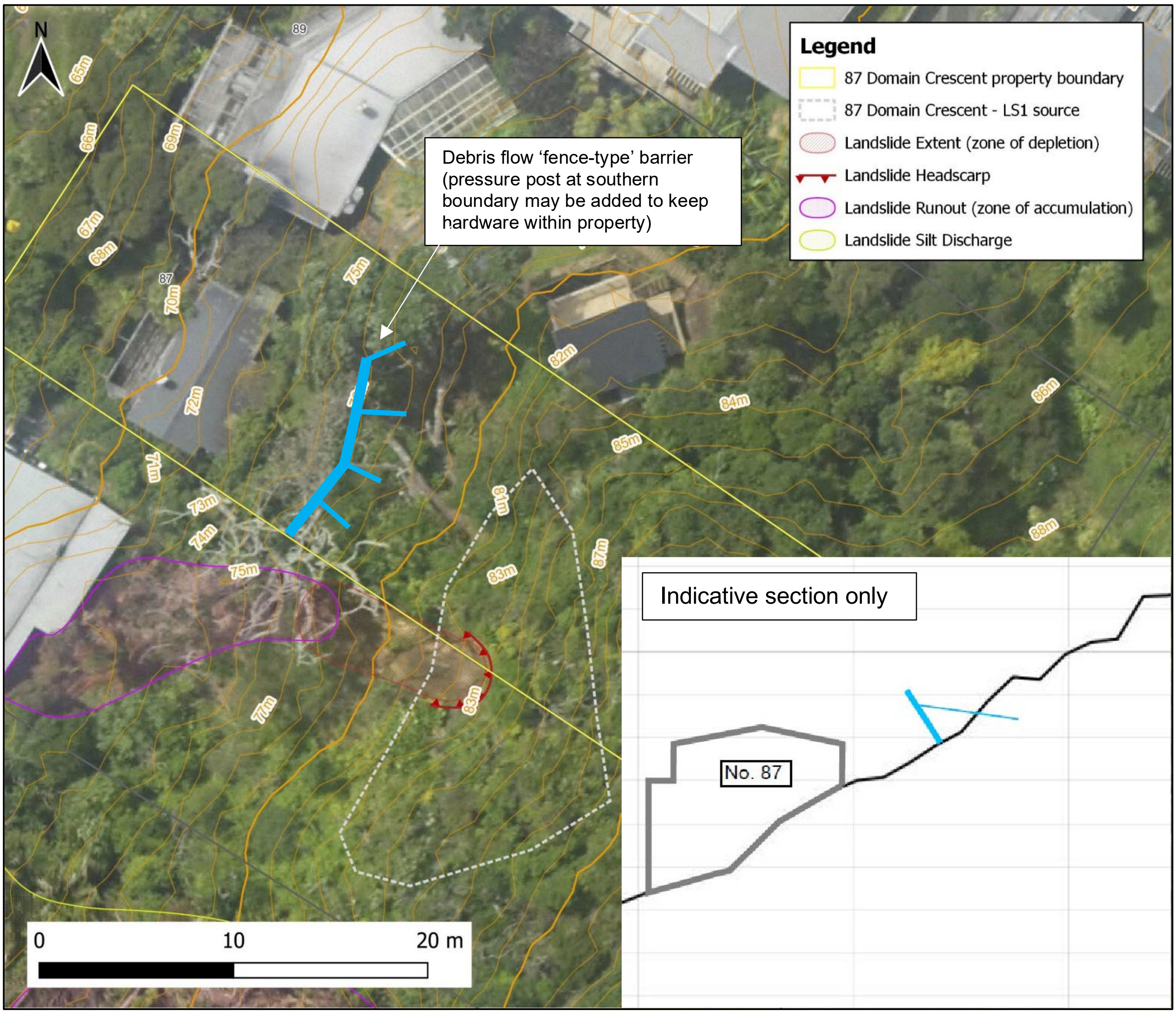


Figure 4.3 *Site plan showing proposed mitigation option for 87 Domain Crescent*

Some of the key site-specific factors to be considered in the design and construction of this mitigation option include:

- Part of the barrier is located outside of the property boundary (within 85 Domain Crescrent).
- Access is considered to be 'hard' as there is no clear access to the proposed barrier location, which is on a slope of approximately 35°. Enabling works are likely required.
- The property is within the Significant Ecological Area (SEA) and damage to trees/vegetation would be likely for both access and construction.
- The subsurface conditions are likely to comprise medium dense to very dense sands overlying massive, extremely weak sandstone.
- Based on an estimated volume of debris of 40 m^3, a fence type barrier height of 3.5 m would be adequate.

4.3 Mitigated loss of life risk estimation

Table 4.1 below presents the resulting risk estimation following implementation of the selected mitigation option. The mitigated risk assessment only considers the failure of the barrier and therefore the spatial probability has been reduced by two orders of magnitude (i.e to 1% probability of failure). This is to reflect the unlikely potential for the barrier to become ineffective and therefore fail to prevent the landslide from reaching the dwelling.

Table 4.1 Summary of unmitigated v mitigated loss of life risk estimation for 87 Domain Crescent

Property	**Hazard**	**Annual probability of the landslide $P_{(H)}$**	**Spatial probability $P_{(S:H)}$**	**Temporal Spatial probability $P_{(T:S)}$**	**Vulnerability $V_{(D:T)}$**	**Unmitigated Risk (from Risk Assessment Report)**	
						Risk $R_{(LOL)}$	**Risk Evaluation**
Unmitigated Risk	LS1	0.01 x 0.05	1.0	0.68	0.8	2.7×10^{-4}	Not tolerable
Mitigated Risk		**0.01 x 0.05**	**0.01**	**0.68**	**0.8**	$\mathbf{2.7 \times 10^{-6}}$	**Acceptable**
Unmitigated Risk	LS1 (Sensitivity case)	*0.02 x 0.05*	*1.0*	*0.68*	*0.8*	5.4×10^{-4}	*Not tolerable*
Mitigated Risk		*0.02 x 0.05*	*0.01*	*0.68*	*0.8*	5.4×10^{-6}	*Acceptable*

Values in italics represent a sensitivity check which considers a higher annual probably of occurrence.

4.4 Mitigation costs

The cost for the proposed mitigation is a high-level estimate based on generic designs. The contingency (uncertainty) is considered high. Geobrugg have provided advice and cost estimates for a flexible debris flow barrier which have been used to inform our total estimate. Whole of life costs have also been considered (e.g. inspections, maintenance).

The total (construct and maintain) P50 expected estimate is in the order of **$215,000** ex GST. An additional cost of $35,000 ex GST for SEA consenting has also been allowed for, giving a total cost of $250,000 ex GST.

We would like to emphasize that the concept and estimated cost presented are high level and indicative only. Further design effort by others is required to better define the details and costs.

5. Conclusion and recommendation

This report has presented the results of a quantitative risk assessment for unmitigated loss of life in relation the property located at 87 Domain Crescent, Muriwai, Waitākere. One landslide hazard (LS1) has formed the basis of this assessment.

Assessment of the most likely future landslide (LS1) estimates the annual risk to loss of life for the person most at risk to be approximately **2.7×10^{-4}**. This risk is higher than the AGS (2007c) suggested tolerable Loss of Life Risk for the person most at risk (see Appendix A).

Detailed in Section 4, a potential remedial measure to lower the risk level associated with future failures (LS1) above the site includes a dynamic flexible fence-type landslide barrier to catch debris upslope of the existing dwelling at an indicative cost of $250,000 ex GST. An estimated mitigated annual risk to loss of life for the person most at risk is approximately 2.7×10^{-6}, which is ‘tolerable’ (AGS 2007c).

As discussed above, this report considers geotechnical matters only. There may be other non-geotechnical considerations that affect final placard designation of which GHD are not aware, such as flood risk and structural damage to property.

We understand AC are currently reviewing their tolerable and acceptable risk criteria for risks associated with landsliding. We recommend Council review the risk assessment presented in this report against the AC risk criteria to assess whether it is appropriate to assess the property risk categorisation and remove or re-assess the current placard designation for the site.

6. Limitations

This report has been prepared by GHD for Auckland Council and may only be used and relied on by Auckland Council for the purpose agreed between GHD and Auckland Council as set out in section 1.2 of this report.

GHD otherwise disclaims responsibility to any person other than Auckland Council arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

The opinions, conclusions and any recommendations in this report are based on assumptions made by GHD described in this report (refer section 1.2 of this report). GHD disclaims liability arising from any of these assumptions being incorrect.

An understanding of the geotechnical site conditions depends on the integration of many pieces of information, some regional, some site specific, some structure specific and some experienced based. Hence this report should not be altered, amended, abbreviated, or issued in part in any way without prior written approval by GHD. GHD does not accept liability in connection with the issuing of an unapproved or modified version of this report.

Verification of the geotechnical assumptions and/or model is an integral part of the design process - investigation, construction verification, and performance monitoring. If the revealed ground or groundwater conditions vary from those assumed or described in this report the matter should be referred back to GHD.

This risk assessment does not mean that there will be no further landsliding impacting this property or group of properties.

Appendix A

AGS (2007) Background

1. Overview

This appendix document outlines the methods and procedures used to estimate risks to loss of life for the person-most-at-risk at the site described in the covering report. This document should be read in conjunction with the covering report as it contains information not presented in the covering report. This document should not be separated from the main report.

2. Landslide Risk Management Framework

2.1 Background

The 1998 Thredbo landslide, in which 18 persons were killed, highlighted the challenges faced from building upon steep slopes and led to the development of the Australian Geomechanics Society Landslide Risk Management guidelines, published in 2007 and now commonly referred to as AGS (2007). The suite of guidelines is recognised nationally (Australia) and internationally as world-leading practice. The reader of this report is encouraged to consult the freely available LRM resources which can be accessed at: https://landsliderisk.org/.

The ”Practice Note Guidelines for Landslide Risk Management” (AGS 2007c), provide technical guidance in relation to the processes and tasks undertaken by geotechnical practitioners who prepare LRM reports including appropriate methods and techniques. The Practice Note is a statement of what constitutes good practice by a competent practitioner for LRM, including defensible and up to date methodologies and provides guidance on the quality of assessment and reporting, including the outcomes to be achieved and how they are to be achieved.

The framework for landslide risk management is presented in the figure below and represents a framework widely used internationally.

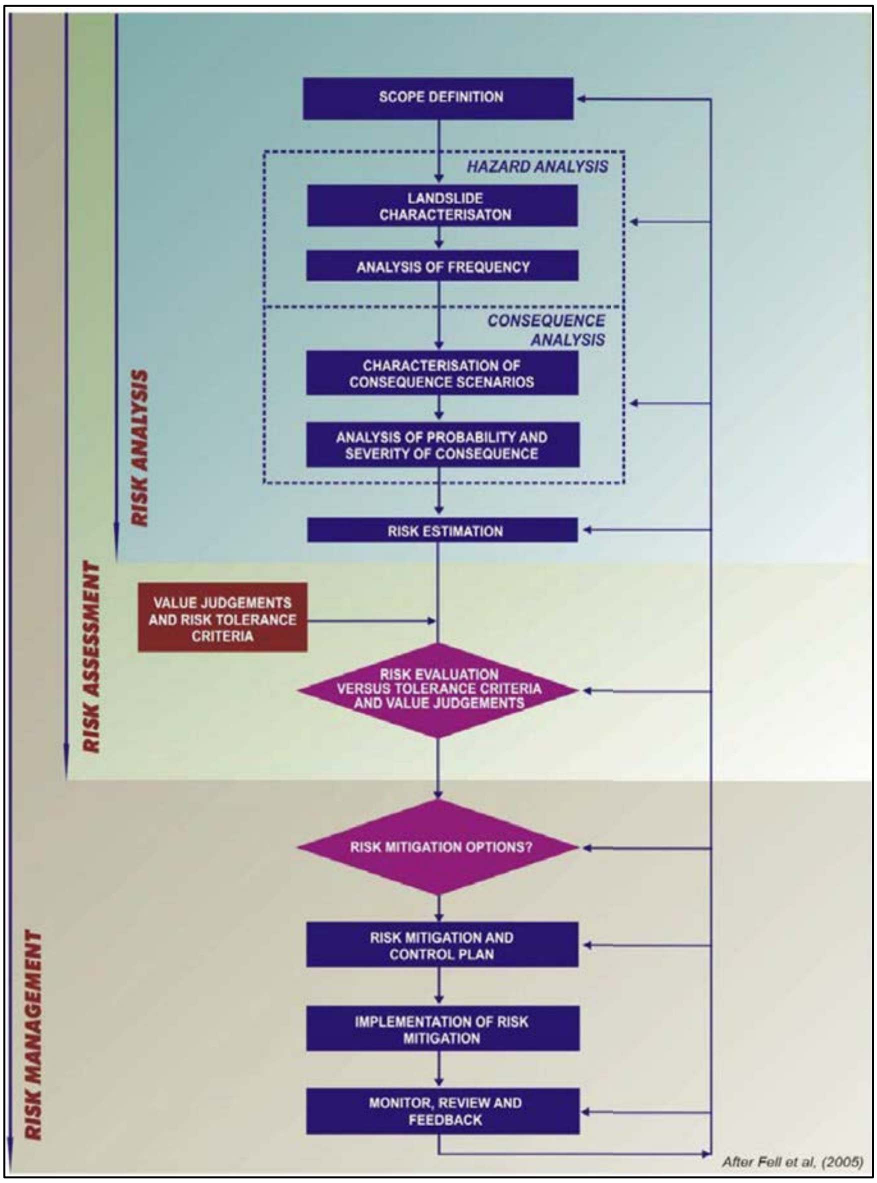


Figure A1 ***Framework for landslide risk management.***

2.2 Risk Estimation Methodology

AGS (2007c) requires risks to loss of life to be estimated quantitatively for the person-most-at-risk. The person-most-at-risk will often but not always be the person with the greatest spatial temporal probability (i.e. the person most exposed to the risk). The Individual Risk-to-Life is defined as the risk of fatality or injury to any identifiable (named) individual who lives within the zone impacted by the landslide; or who follows a particular pattern of life that might subject him or her to the consequences of the landslide. The risk of 'loss-of-life' to an individual is calculated from:

$$\mathbf{R}_{(LoL)} = \mathbf{P}_{(H)} \times \mathbf{P}_{(S:H)} \times \mathbf{P}_{(T:S)} \times \mathbf{V}_{(D:T)}$$

Where:

$\mathbf{R}_{(LoL)}$ is the risk (annual probability of death of an individual).

$\mathbf{P}_{(H)}$ is the annual probability of the landslide (event).

$\mathbf{P}_{(S:H)}$ is the probability of spatial impact of the event impacting an individual taking into account the travel distance and travel direction given the event. For example, the probability of an individual in a building or in the open being impacted by a rockfall / landslide at a given location.

$P_{(T:S)}$ is the temporal spatial probability (e.g. of the building or location being occupied by the individual at the time of impact) given the spatial impact and allowing for the possibility of evacuation given there is warning of the event occurrence.

$V_{(D:T)}$ is the vulnerability of the individual (probability of loss of life of the individual given the impact).

2.3 Landslide Risk Assessment Uncertainty

The process of risk assessment involves estimation of likelihood, consequence and risks based on available information for the study site. By its very nature, much of the data, including historical and current inventories may be incomplete whilst an understanding of the triggering events has a degree of uncertainty attached to it. Judgement is required to estimate the nature and size of potential hazards, their frequency of occurrence and their impact on a variety of elements at risk. As these judgements are based on the knowledge, experience and understanding of the assessor, it is not unusual for different assessors to make different judgements about the level of risk.

The thought process used in establishing likelihoods, consequences and determining spatial and temporal factors for properties has been documented for transparency. The structure of the risk assessment process is well defined and values for some input parameters have been tabulated to guide standard approaches by different assessors. However, this should not be mistaken for precision given the limitations of the inputs outlined above. Generally, the levels of likelihoods and risks should be thought of as being within a range of typically +/- half an order of magnitude.

While the basis for the judgements contained in this report are well documented, and the levels of risk considered to be good representations of reality, the accuracy and precision of the process should not be overestimated and should always be used in an appropriate manner in combination with risk management including mitigation and treatment options.

3. Hazard Characterisation

AGS (2007c) generally states that all credible hazards originating on, above and below the sites should be assessed. This is generally a predictive exercise based on knowledge and understanding of the geological and geomorphological setting with a view to assembling historical evidence for past hazard events.

3.1 Defining the Most Likely Significant Landslide

Following Cyclone Gabrielle, small landslides within the Muriwai area were often noted to be shallow translational slides developed in the upper residual profile of the Awhitu Sand Formation which, under saturation, transition into debris flows. Detailed analysis by GHD of the mapped landslides within the Karekare and Piha areas, which included size, estimated volume, travel distance and travel angle, was undertaken to characterise the nature and distribution of landslides following the rainfall events that occurred in early 2023, particularly the Cyclone Gabrielle rainfall event, has been used as a basis for defining the magnitude of the ‘most significant landslide’ for the site.

A total of 80 landslides were mapped throughout Karekare and Piha following the storm events in Jan and Feb 2023. These landslides were then grouped into categories of volume in 50 m^3 increments. Results for an assessment of “frequency as categorised by volume” is shown in Figure 1 below.

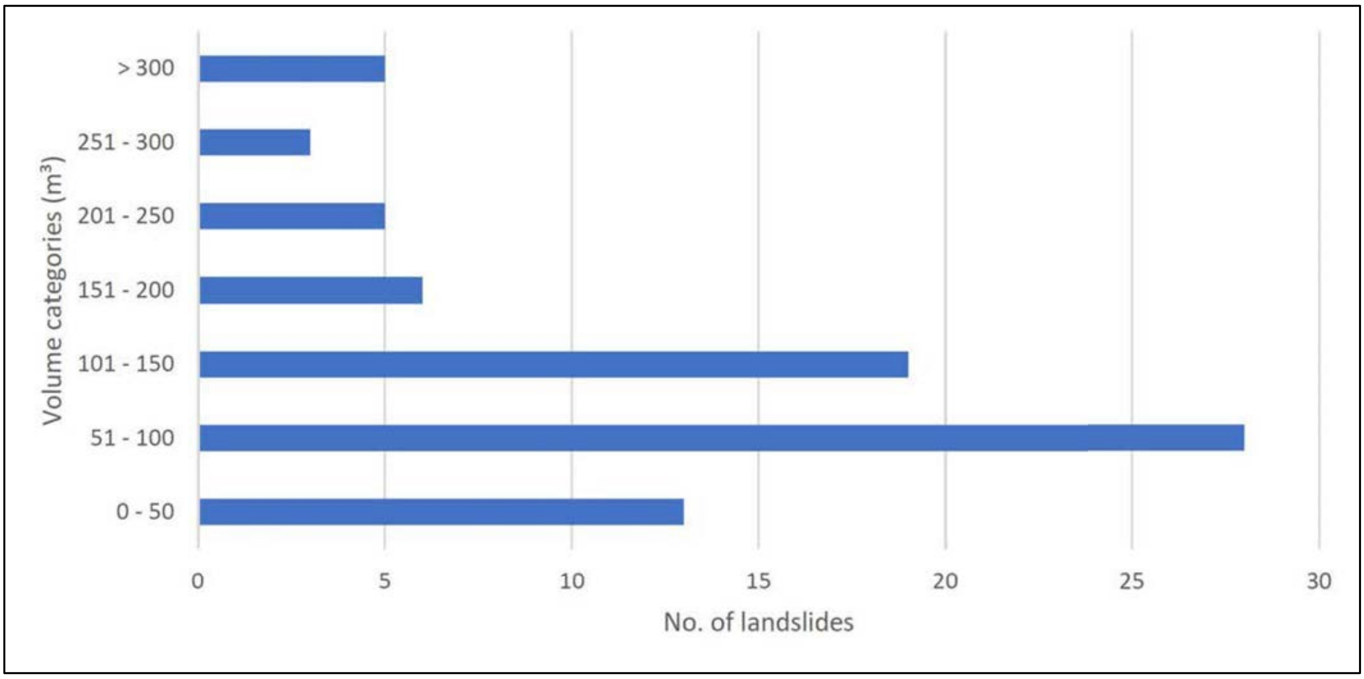


Figure A2 ***The number or frequency of mapped debris flows (on the x axis) as categorised by volume increments for mapped source areas of debris flows (on the y axis in m^3) in Karekare and Piha.***

In addition, detailed information regarding volume size, travel angle, travel distance, confinement (either unconfined or channelized) and the degree of damage caused by slides impacting dwellings and building was also collated and a number of additional graphs were developed as below:

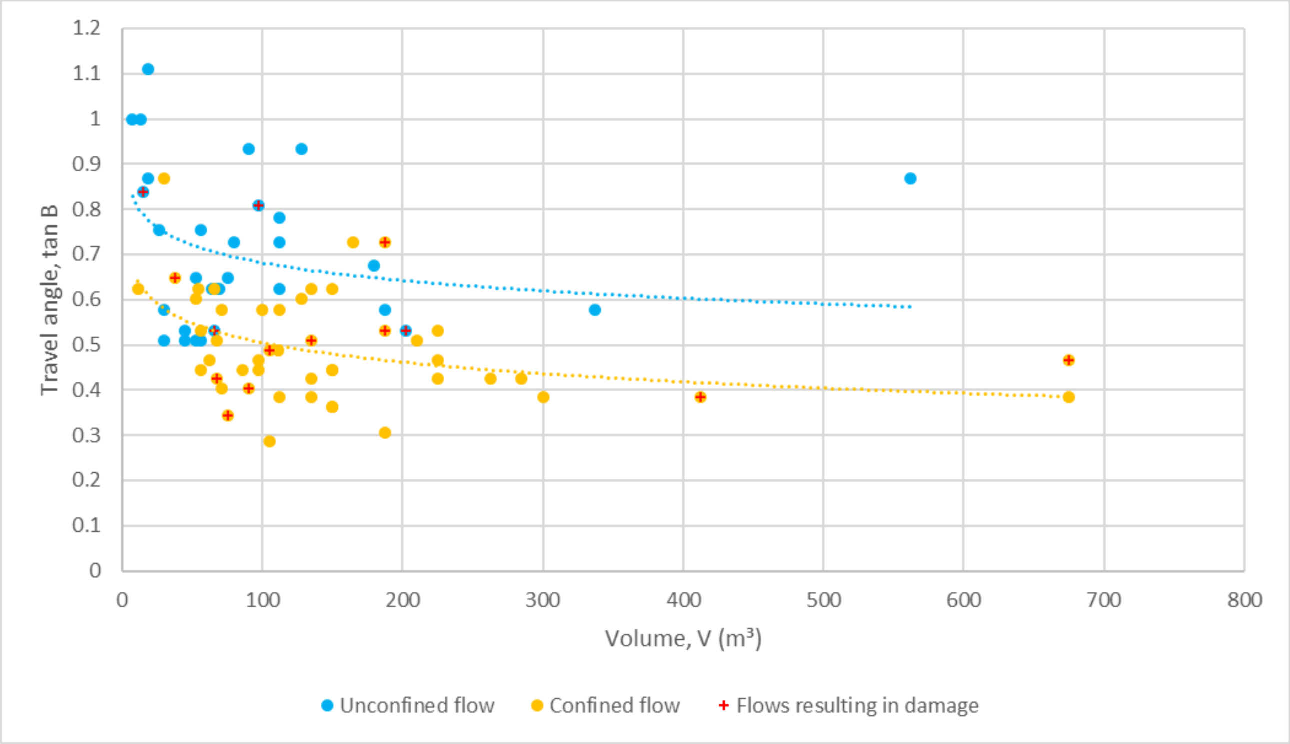


Figure A3 ***Travel angle vs volume of source area for the Karekare and Piha debris flows***

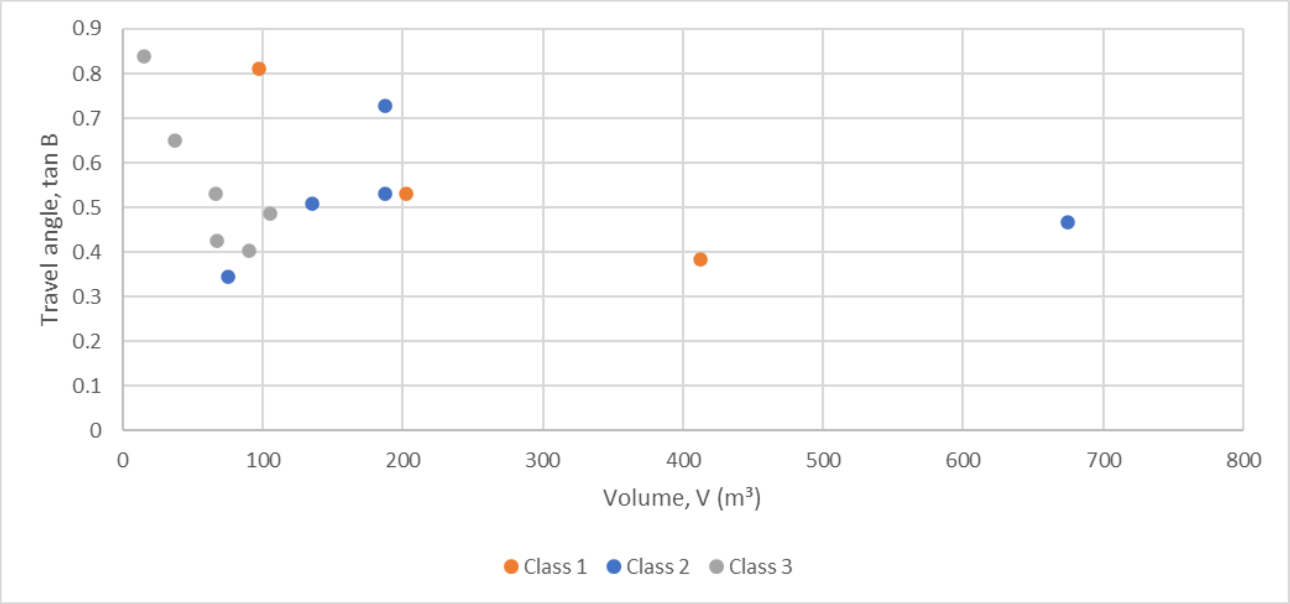


Figure A4 ***Plot of only those debris flows known to have caused some degree of damage to dwellings and buildings. Note Class 1 = Complete destruction/collapse of building, Class 2 = Partial destruction/collapse of building, significant inundation and Class 3 = Limited damage to building but no collapse or inundation, damage is other property infrastructure e.g., access stairs.***

This assessment highlights a number of important points relating the nature of these hazards including:

- Whilst a range of volumes of source areas for debris flow was noted, the most common or likely sized event was of the order of 50-100 m^3 as determined by the frequency plot.
- Many smaller volume source areas for debris flows (less than 75 m^3) typically only caused some lesser damage to buildings but once the volume increased above 100 m^3, then the vast majority of debris flows were noted to have caused partial or full collapse of dwellings and buildings.
- The greater the volume of the source area, the lower the travel angle and the greater the runout or travel distance.
- Unconfined debris flows generally have a higher travel angle compared to confined or channelized debris flows of the same volume. This means that confined or channelised debris flows have a longer runout or travel distance and hence have more potential to impact elements at risk further down the slope.

Based on this site-specific data and analysis, GHD has adopted a working definition for these risk assessments of what is termed the **most likely significant landslide** as follows:

- The volume of most likely significant landslides is assumed to be 100 $m^{3.}$
- This volume has been shown to cause significant building damage resulting in partial to full dwelling and building collapse.
- As a result, this hazard is considered to have a high probability for causing loss of life.
- Where this hazard is unconfined, the adopted travel angle based on Figure 3 has been taken as Tan (B) = 0.69 or approx. = 35°
- Where this hazard is confined or channelised the adopted travel angle based on Figure 3 has been taken as Tan (B) = 0.50 or approx. = 26.5°
- Comparison with Figure 6 from Hunter and Fell (2002) suggests the site derived travel angles are generally consistent with other data presented in that plot.

The definition of the **most likely significant landslide** is considered to be a reasonably conservative but not overly cautious estimate of the potential hazard that may affect the site. This is based on an assessment of an overview of landslides that GHD has observed in Muriwai, Karekare and Piha in 2023.

It is noted however that in some specific circumstances, larger recent debris flows may have occurred in close proximity to the site under investigation. As such, where there is evidence for a larger hazard, the assessor may

choose to adopt a larger volume event based on judgement and knowledge of that particular site. In this case other values for travel angle can be read from Figure 3.

IMPORTANT NOTE: It is duly acknowledged that volume alone does not necessarily account for the full potential of a debris flow to cause significant damage and other factors such as the degree of channelization, the additional entrainment of volume within a channel, the degree of saturation of the debris materials, the location of the source area on the hillslope, the direction of travel, the distance of travel and the velocity of the hazard at the point of impact all play important roles in the destructive capacity of any debris flow. Some of these factors are considered within the risk assessment process as conditional probabilities in spatial considerations.

3.2 Description of Other Landslide Types

As discussed in the scope of the covering report, other landslide hazards may exist at the site under assessment. These may include existing geohazards that have resulted from recent failures with the potential to pose risk to life in the immediate short-term (i.e. within the next few years) such as regression of translational failures to occur downslope of dwelling, failure of over-steepened fill and cut slopes, rockfall hazards associated with exposed rock faces/headscarps and/or loose debris remaining upslope of dwellings.

In addition, other possible geotechnical slope instability hazards relating to modified slopes (i.e. human made) may also exist and have potential to pose a risk to life - such as failures of fills, cuttings and failed retaining walls. This represents hazards that may have a range of likelihood from almost certain to possible.

Where appropriate, descriptions and definitions for each of these hazards are provided in the covering report on a case-by-case basis and will be specific to the observed hazard and actual conditions at this site.

3.3 General Descriptors for Size Classification of Landslides.

Generalized or relative descriptions of size classification systems for landslides vary significantly depending on the country of origin and the nature of the landslide hazards typically encountered. For the purposes of these assessments, GHD proposes to use the following size classification descriptions adopted from the Transport for New South Wales (TfNSW) Guide to Slope Risk Analysis Version 4 (TfNSW 2014) (see Table 3.1 below).

Table A3.1 Landslide size classification

Relative size term	Volume range	Typical mid-range dimensions (width x length x depth in metres)
Very small	<20 m3	4 x 4 x 0.5
Small	20 to 200 m3	10 x 10 x1
Medium	200 to 2000 m3	20 x 20 x 2.5
Large	2000 to 20000 m3	40 x 40 x 5
Very large	>20,000 m3	60 x 60 x 8

4. Likelihood $P_{(H)}$

Likelihood or annual probability of occurrence of the landslide, $P_{(H)}$, is one of the most critical but difficult to estimate factors as part of the risk assessment process.

4.1 The Most Likely Significant Landslide

The recent flood / storm events, the estimation of recurrence intervals for that event and the occurrence of the observed hazards form the basis for the current estimated probability of occurrence for the most likely significant landslide hazard. However, observations of the recent events noted that not all similar slopes failed as a result of

the initiating storm event and as such, an additional consideration for probability of occurrence has been included within the analysis by using conditional probabilities as follows:

$$P_{(H)} = P_{(H'1)} \times P_{(H'2)}$$

Where:

$P_{(H'1)}$ = Probability that the rainfall threshold for the most credible significant landslide is exceeded which is taken as a proxy for landslide initiation. This is assumed to be 1 in 100 or 0.01 (see analysis and discussion by Auckland Council below) or 1 in 50 or 0.02 under the influence of future climate change.

$P_{(H'2)}$ =Probability that the slope for the specific assessment fails, which relates to how many of the actual slopes failed out of the total number of all slopes present. This probability is typically based a on spatial analysis of the total area of failed landslides slopes compared to the total area of all slopes for the geomorphic setting in which the site is located.

4.2 Auckland Council Guidance on Frequency for Most Likely Significant Landslide

Council provided GHD with an assessment of available rainfall data associated with Cyclone Gabrielle (Auckland Council 2023) (AC memo). During Cyclone Gabrielle, the tipping bucket rain gauge at Muriwai failed and was inundated by flood waters. The AC memo also provided rainfall analysis using AC's Quantitative Precipitation Estimate (QPE) Rain Radar System, which is a real-time rainfall product that utilises the MetService radar. The rainfall data presented by AC indicates a peak rainfall total for Muriwai during the event of 146.9mm, occurring over 12-hour period. This total is >100-year event at a 12-hour duration. The data suggests that for the 12-hour duration rainfall, the Annual Recurrence Interval (ARI) is >100 years and may be in the order of 250 years. However, we understand that the calculation above the 100-year assessment becomes increasingly unreliable, primarily as a result of the relatively short statistical rainfall records available in New Zealand. For the other durations modelled, the rainfall was below the 100-year event.

The AC memo recommended that an envelope of "risk" is estimated as the ARI figures will change over time and as these events are incorporated into the statistical record. The AC memo states that in general, it is considered reasonable to consider the Cyclone Gabrielle event to be in the range of 100-250 year ARI. For this assessment we have assumed that the annual likelihood of a landslide event occurring that is similar in magnitude to the February 2023 event, is about 1 in 100 (i.e., 0.01). This is considered to have a *likely* probability of occurrence.

The assumption of 1 in 100 based on rainfall frequency is a simplifying and possibly conservative assumption that we consider reasonable. It does not consider other factors that could potentially affect stability (antecedent conditions, geology, groundwater conditions, slope height and angle, vegetation, surface water management-overland flow path, overflow from water storage tanks, effect of effluent disposal field), all of which are difficult to quantify.

The AC memo further recommended that risk assessment reports consider the potential for climate change to increase the frequency of high intensity rainfall. We understand that the National Institute of Water and Atmospheric Research (NIWA) has projected a 20% increase in rainfall intensity over the next 100 years which suggests that a 250-year ARI event could increase to a 50-year ARI event. Consequently, we have also included a sensitivity check based on a 50-year ARI event.

We draw the reader's attention to Section 3 of this report and reiterate that AGS (2007c) generally states that all credible hazards originating on, above and below the sites should be assessed. This report has conformed to this requirement and assessed landslide hazards that were observable during the site mapping and/or able to be interpreted via other means such as readily available aerial photographs, lidar data etc. It should be recognised that specific hazards such as rockfalls, failed retaining walls, over-steepened cuts/fill batters may have likelihoods in the *Certain to Almost Certain* range and are more likely to occur in the short term.

4.3 Other Landslide Hazards

Where other slope failures and instabilities as described in Section 3.2 are considered, individual assessments of $P_{(H)}$, the probability of occurrence, are made on the basis of expert judgment, performance of similar landslides in the area and recent site observations.

When considering hazards that may pose immediate or short-term risks to life it is probable that such hazards will have high likelihoods of occurrence that could be triggered by relatively frequent events. As a result, such hazard may have likelihoods in the *Certain to Almost Certain* range as per the ASGS2007 qualitative descriptors for likelihood.

5. Probability of Spatial Impact $P_{(S:H)}$

The AGS definition of spatial probability is represented by single term $P_{(S:H)}$ and is described as the probability of spatial impact by the landslide on the element at risk, given the landslide occurs and taking into account the travel distance and travel direction.

5.1 The Most Likely Significant Landslide - Upslope of Site

A number of conditional factors may be involved in the spatial distribution for the most likely significant landslide, and for further transparency, the following methodology has been adopted:

$$P_{(S:H)} = P_{(S':H'1)} \text{ x } P_{(S':H'2)}$$

Where:

- $P_{(S':H'1)}$ = The probability that if the landslide occurs it travels in the direction of the site under assessment. If the slopes above are consistent, and planar then probability is assumed to be 0.8 to 1.0 depending on the topography; if the originating landslide enters a channel that is directed onto the property then probability is assumed to be 1.0, or if the landslide enters a channel that is directed away from the sites then the probability is assumed to be 0.05 taking account of a small probability that the landslide may super elevate and leave the channel.
- $P_{(S':H'2)}$ = The Probability that if the landslide occurs it will travel to at least the site under assessment and will impact the property. This is to be based on two considerations as follows:

    1. Modelled Behaviour based on travel distance analysis undertaken by GHD for 80 observed landslides slides in the Karekare and Piha areas (see Figure A3). Either probability = 1.0 if the travel angle projects past the dwelling, = 0.5 if the travel angle projects to the rear of the dwelling or = 0.0 if the travel angle falls short of the dwelling.

And/or

2. Observational behaviour: based on site observations of whether the previous landslides within close proximity to the study site, travelled sufficient distance to reach the site under assessment; if yes Probability = 1.0, if no, then probability = 0

- NOTE 1: The GHD analysis of travel distance highlights the effect of channelisation which shows confined debris flows travel further (i.e., they have a lower travel angle) than those which are unconfined on consistent or planar slopes. Such considerations are included on a site-by-site basis. Interestingly, this event-specific analysis also generally agrees with findings presented in Hunter and Fell (2002).
- NOTE 2: Where significant debris flows have occurred in close proximity to the site under assessment, and the observed travel distance is greater than that estimated using the modelled approach, the preferred GHD approach is to use the greater of the two travel distances to assess spatial impact.

5.2 The Most Likely Significant Landslide – Under the Dwelling/Building and/or Downslope Below the Dwelling/Building

Based on the possible failure area:

- If the failure area is > ~5 m from the dwelling then the value for $P_{(S:H)}$ will be 0 as a landslide occurring at that location will not impact dwelling. (The general assumption is that the landslide headscarp would have a length of 5m based on size of most likely significant landslide).
- If the failure area is within ~5m from the dwelling (like above) then the value for $P_{(S:H)}$ will be 0.5 to account for uncertainty of it encroaching within the footprint of the dwelling.
- If the failure area encompasses a significant portion of the dwelling then the value for $P_{(S:H)}$ will be 1.0 as there is a certain probability it will impact the dwelling.

Estimates of how far back the most significant landslide will regress are difficult to model without a detailed slope stability analysis and sufficiently accurate soil and rock inputs. This would require an intrusive geotechnical investigation which is outside the scope of this study.

GHD has adopted a more empirical approach that assesses the spatial extent of lateral downslope movement of the most likely significant landslide based on direct observations of existing landslides in close proximity to the site under assessment. In the absence of other information, a similar extent of regression has been applied to any future slides. An estimate of $P_{(S:H)}$ can then be made as to the potential interaction with the element at risk.

5.3 Other landslides – Upslope of the study site

Other types of potential landslides situated above dwellings and buildings on the site under assessment, should be assessed in a similar manner to the most likely significant landslide. Estimates of travel distance are taken from Hunter and Fell (2002) and/or previous local knowledge and/or observation of similar landslides in the area.

When undertaking short term assessments, hazards involving reactivation of existing landslides that are located upslope of the study site that didn’t previously reach the site must be taken account. In addition, remobilisation of debris from any upslope landslides must also be assessed for their potential of runout or travel distance using Hunter and Fell (2002).

Similarly potential failures of modified slopes such as cuttings or fills located above or directly adjacent to dwellings and buildings must also be assessed for their spatial impact and the methods of assessment follow the same approach.

5.4 Other landslides – under buildings and downslope of the building

A similar approach to that taken for other landslides upslope has been adopted. Observation of existing failures and how much lateral downslope movement can be used as a proxy for what may occur in the future under a regression type scenario.

5.5 Temporal Spatial Probability $P_{(T:H)}$

These risk assessments have not considered specific occupancy scenarios for each individual residence. We acknowledge that the occupancy of each residence could vary significantly depending on the demographics of the residents and the usage of the residence. For example, some residences may be predominantly used as holiday accommodation, occupied mainly on weekends, whereas other residences could be permanently occupied by working families.

This assessment has assumed the following occupancies:

- Residences are typically occupied for 15 hours each day during weekdays;
- On weekends, residences are occupied for about 20 hours each day;

– The percentage of time a residence is occupied is therefore about 68%.

Any further delineation of the spatial variations in occupancy (i.e. if a bedroom is at the front or the rear of the house etc) are not considered feasible or warranted within the context of the precision of this assessment.

6. Vulnerability $V_{(D:T)}$

6.1 Most likely significant Landslide

AGS (2007c) includes a table of vulnerability values for various inundation and building damage scenarios as adapted by Finlay et al (1999). It is important to note that the AGS (2007c) vulnerability table doesn't adequately cater for all the building damage scenarios GHD has observed in Muriwai, Karekare and Piha. GHD has therefore further adapted this table and combined it with information from the TfNSW Guide to Slope Risk Analysis (2014) as well as observations of damage to buildings and structures resulting from the recent landslides in Muriwai, Karekare and Piha.

The table of vulnerability values used in this assessment is presented in Table A6.1. These values have been used as a guide and expert judgement has been applied to select a value within the range of values where appropriate on a site-specific basis.

Table A6.1 Summary of Vulnerability Values adopted

Case	Range	Typical value to be used in this assessment	Comments
Person in a building that collapses under impact from debris flow	0.8 -1.0	0.9	Death is almost certain. Evacuation unlikely to occur
If building is inundated with debris and the person is buried	0.8 -1.0	0.8	Very high potential for death Evacuation unlikely to occur
If building is inundated with debris but no collapse occurs and the person is not buried	0.01 -0.1	0.1	High chance of survival Evacuation unlikely to occur
If the debris strikes the building only	0.001-0.05	0.01	Very high chance of survival
If failure occurs below the building and results in significant collapse	0.5-0.8	0.6	Moderate to high potential for death. No forewarning signs with evacuation unlikely to occur.
If failure occurs below the building and results in partial collapse	0.01 -0.1	0.05	High chance of survival. Signs of building distress should provide occupants with opportunity to take evasive action.
If failure occurs below the building and results in damage. No collapse occurs.	0.001-0.05	0.005	Very high chance of survival. Evacuation almost certain.

7. Risk Evaluation

The main objectives of risk evaluation are usually to compare the assessed risk to risk levels that are acceptable or tolerable to the community, and therefore to decide whether to accept, tolerate or treat the risks and to set

priorities for remediation. The Tolerable Risk Criteria are usually imposed by the regulator, unless agreed otherwise with the owner/client. AGS (2007d) provides discussion and gives the AGS recommendations in relation to tolerable risk for loss of life. These are summarized in the table below.

Table A7.1 AGS Suggested Tolerable loss of life individual risk.

Situation	Suggested Tolerable Loss of Life Risk for the person most at risk
Existing Slope / Existing Development	10^{-4} per annum (1E-4 pa) or 1 in 10,000 pa
New Constructed Slope / New Development / Existing Landslide	10^{-5} per annum (1E-5 pa) or 1 in 100,000 pa

It is important to distinguish between "acceptable risks" and "tolerable risks". AGS (2007c) states that tolerable risks are risks within a range that society can live with so as to secure certain benefits. It is a range of risk regarded as non-negligible and needing to be kept under review and reduced further if practicable. Acceptable risks are risks which everyone affected is prepared to accept. Acceptable risks are usually considered to be one order of magnitude lower than the Tolerable risks.

8. References

Auckland Council (2023). 'Guidelines on the use of AGS (2007) for landslide risk assessment in Auckland following the 2023 flooding and cyclone'. Memorandum dated 20 September 2023.

Australian Geomechanics Vol 42 No 1 March 2007 Extract "Practice Note Guidelines for Landslide Risk Management 200" AGS (2007c)

P J Finlay, G R Mostyn & R Fell (1999). 'Landslides: Prediction of Travel Distance and Guidelines for Vulnerability of Persons'. Proc 8th. Australia New Zealand Conference on Geomechanics, Hobart. Australian Geomechanics Society, ISBN 1 86445 0029, Vol 1, pp.105-113.

Hunter. G., & Fell. R. (2002).' Estimation of Travel Distance for Landslides in Soil Slopes'. Australian Geomechanics, Vol 37, No2.

New South Wales Government, Transport for New South Wales 'Guide to Slope Risk Analysis' Version 4, April 2014.

Appendix B

Glossary of Terms

DEFINITION OF TERMS

Acceptable Risk – A risk which, for the purposes of life or work, society is prepared to accept as it is with no regard to its management. Society does not generally consider expenditure in further reducing such risks justifiable~~.~~

Authority or **Council** having statutory responsibility for community activities, community safety and development approval or management of development within its defined area/region

Consequence – The outcomes or potential outcomes arising from the occurrence of a landslide expressed qualitatively or quantitatively, in terms of loss, disadvantage or gain, damage, injury or loss of life.

Creep Failure – A time-dependant deformation mechanism where constant stress is applied to a material. Creep failure can be identified by ridges the ground surface and curved tree trunks.

Dropout – A landslide feature occurring along the length of the road-side on the downslope edge. Drop outs can result in the undermining the road carriageway.

Elements at Risk – The population, buildings and engineering works, economic activities, public services utilities, infrastructure and environmental features in the area potentially affected by landslides.

Entrainment – The process of surface sediment transportation through water and mass movement.

Frequency – A measure of likelihood expressed as the number of occurrences of an event in a given time. See also Likelihood and Probability of Occurrence.

Hazard – A condition with the potential for causing an undesirable consequence. The description of landslide hazard should include the location, volume (or area), classification and velocity of the potential landslides and any resultant detached material, and the probability of their occurrence within a given period of time.

Individual Risk to Life – The risk of fatality or injury to any identifiable (named) individual who lives within the zone impacted by the landslide or who follows a particular pattern of life that might subject him or her to the consequences of the landslide.

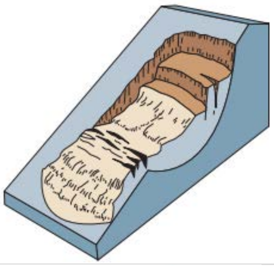
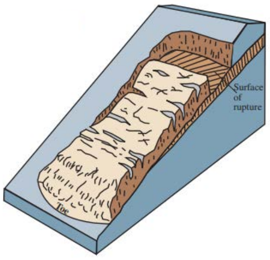
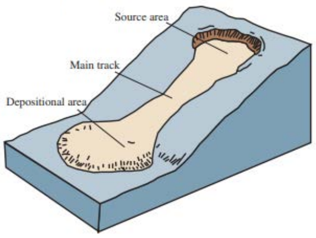
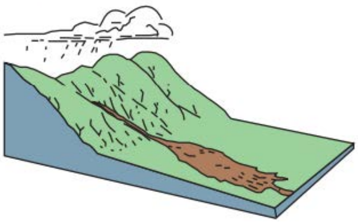
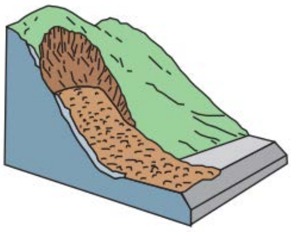
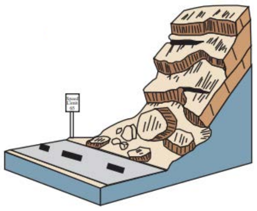
Landslide - A landslide is defined as the movement of a mass of rock, debris, or earth down a slope. The most widely used landslide classification system is that proposed by Cruden and Varnes in 1996 (after Varnes 1954 and Varnes 1978). This has been updated by Hungr, et al., 2014. In its most simple form two nouns are used to describe, firstly the type of material involved and secondly, the mechanism of failure, i.e., rock fall, debris flow.

Landslide inventory – An inventory of the location, classification, volume, activity and date of occurrence of landsliding

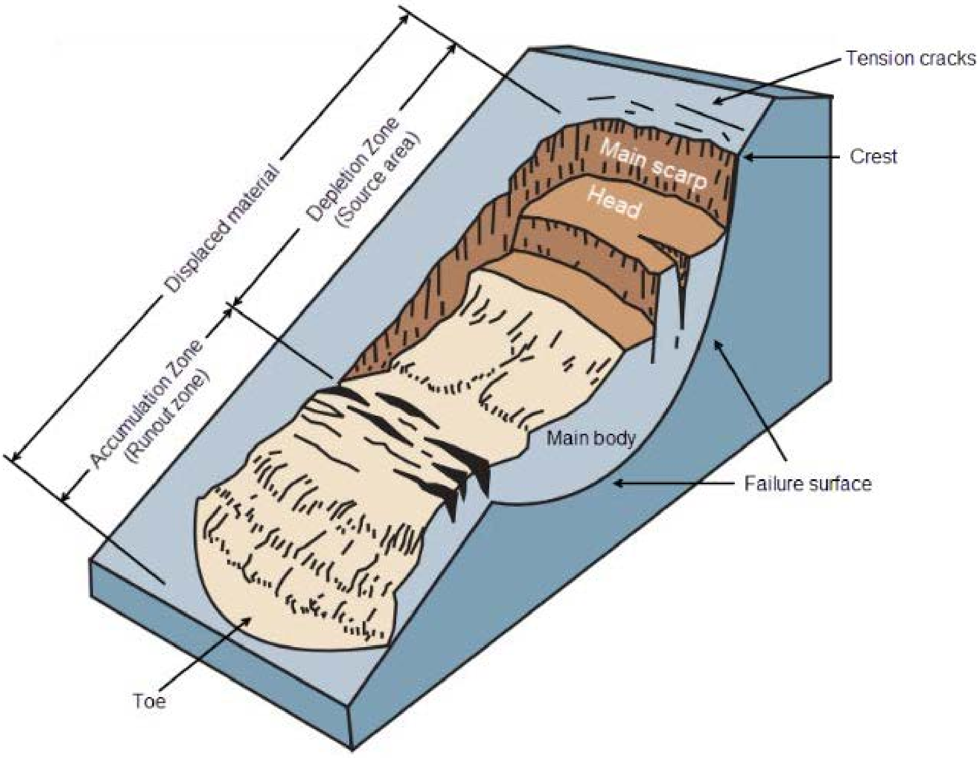
Landslide Risk - Landslide risk is defined herein as the likelihood that a particular landslide will occur and the possible consequences to a specific element at risk (property or human life) taking account of both spatial and temporal considerations.

Landslide Susceptibility – A quantitative or qualitative assessment of the classification, volume (or area) and spatial distribution of landslides which exist or potentially may occur in an area. Susceptibility may also include a description of the velocity and intensity of the existing or potential landsliding.

Landslide Classification – Referenced from Varnes, 1978.

Landslide Type	Landslide Description	Illustration
Rotational sliding	The landslide failure surface is curved concavely upward and the movement of mass is mainly rotational. Rotational movement causes back tilting of the displaced material near the headscarp.	
Translational sliding	The landslide mass moves along a planar failure surface with minor rotational movement.	
Earth flow	The movement of saturated fine-grained materials or clay bearing rocks. The displaced material forms a characteristic hourglass shape with an elongated flow path.	
Debris flow	The rapid movement of saturated, loose material caused by heavy precipitation and surface water flow. Commonly occurring on steep slopes.	
Debris avalanche	A type of debris flow that is *extremely* rapid.	
Rock fall	The separation of rocks and boulders along fractures, joints and bedding planes on steep slopes or cliffs. The movement is heavily influenced by mechanical weathering of the rock mass and gravity.	

Landslide characteristics – Modified after Varnes, 1978.



Likelihood – Used as a qualitative description of probability or frequency of the event/landslide.

Overland Flow Path – The predicated flow path of stormwater over the topography.

Permeability – The capacity of a material to allow water to pass through it. Clay materials are impermeable whereas gravels and sands are porous and therefore permeable.

Probability – A measure of the degree of certainty. This measure has a value between zero (impossibility) and 1.0 (certainty). It is an estimate of the likelihood of the magnitude of the uncertain quantity or the likelihood of the occurrence of the uncertain future event. There are two main interpretations:

(i) Statistical – frequency or fraction – The outcome of a repetitive experiment of some kind like flipping coins. It also includes the idea of population variability. Such a number is called an “objective” or relative frequentist probability because it exists in the real world and is in principle measurable by doing the experiment.
(ii) Subjective probability (degree of belief) – Quantified measure of belief, judgement, or confidence in the likelihood of a outcome, obtained by considering all available information honestly, fairly and with a minimum of bias. Subjective probability is affected by the state of understanding of a process, judgement regarding an evaluation or the quality and quantity of information. It may change over time as the state of knowledge changes.

Probability of Occurrence – used interchangeably with Likelihood.

Quantitative Risk Analysis – an analysis based on numerical values of the probability, vulnerability and consequences, and resulting in a numerical value of the risk.

Recurrence Interval (repeat period) – An estimated value of how often an event occurs based on the average time between passed events.

Regression – The continual movement of a landslide downslope and or widening/retreat of the headscarp.

The **Regulator** will be the responsible body/authority for setting Acceptable/Tolerable Risk Criteria to be adopted for the community/region/activity, which will be the basis for setting levels for Acceptable and Tolerable Risk in the application of the risk assessment guidelines.

Risk – A measure of the probability and severity of an adverse effect to health, property or the environment. Risk is often estimated by the product of probability x consequences. However, a more general interpretation of risk involves a comparison of the probability and consequences in a non-product form.

Risk Analysis – The use of available information to estimate the risk to individuals, population, property or the environment from hazards. Risk analyses generally contain the following steps: scope definition, hazard identification and risk estimation.

Risk Assessment – The process of risk analysis and risk evaluation.

Risk Control or Risk Treatment – The process of decision making for managing risk and the implementation or enforcement of risk mitigation measures and the re-evaluation of its effectiveness from time to time, using the results of risk assessment as one input.

Risk Estimation – The process used to produce a measure of the level of health, property or environmental risks being analysed. Risk estimation contains the following steps: frequency analysis, consequence analysis and their integration.

Risk Evaluation – The stage at which values and judgements enter the decision process, explicitly or implicitly, by including consideration of the importance of the estimated risks and the associated social, environmental, and economic consequences, in order to identify a range of alternatives for managing the risks.

Risk Management – The complete process of risk assessment and risk control (*or risk treatment*).

Runout Distance – The horizontal distance from the source area to the distal toe.

Susceptibility – see Landslide Susceptibility

Temporal-Spatial Probability – The probability that the element at risk is in the affected area at the time of the landslide.

Tolerable Risk – A risk within a range that society can live with so as to secure certain net benefits. It is a range of risk regarded as non-negligible and needing to be kept under review and reduced further if possible.

Transgression-regression cycles – Sedimentary deposits formed from cycles of sea level rise and fall.

Travel Angle – The angle from the crest of the source area to the distal toe of the debris (run out zone)

Vulnerability – The degree of loss to a given element or set of elements within the area affected by the landslide hazard. It is expressed on a scale of 0 (no loss) to 1 (total loss). For property, the loss will be the value of the damage relative to the value of the property; for persons, it will be the probability that a particular life (the element at risk) will be lost, given the person(s) is affected by the landslide.

ghd.com

→ The Power of Commitment

Appendix E-4

207 Motutara Road Landslide Risk Assessment

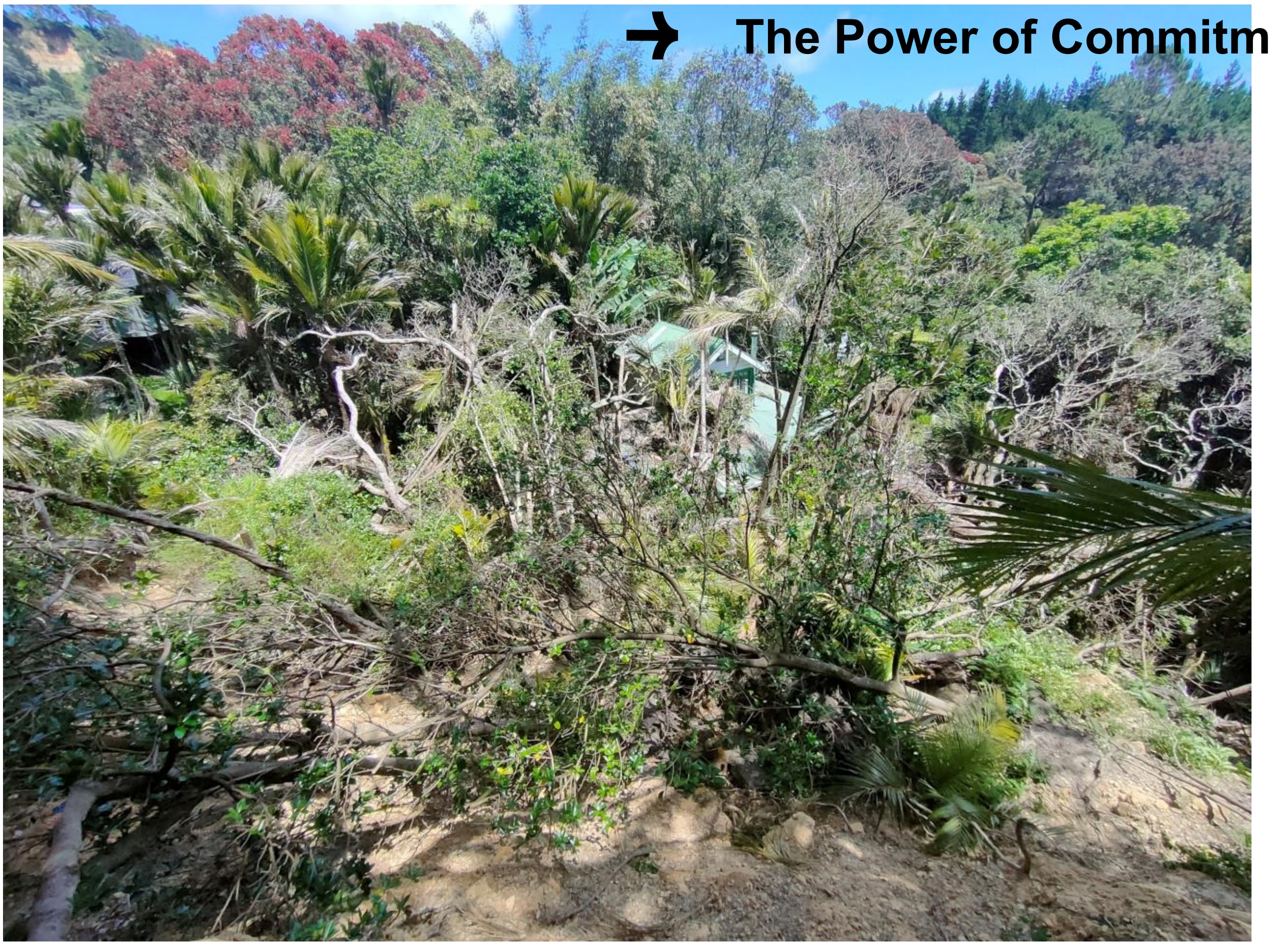
Waitākere Coastal Communities Landslide Risk Assessment

207 Motutara Road, Muriwai

Auckland Council

30 April 2024

➜ The Power of Commitment



<table>
<tr><th>Project name</th><td colspan="7">AC Geo Panel - Waitākere Coastal Communities LHRA</td></tr>
<tr><th>Document title</th><td colspan="7">Waitākere Coastal Communities Landslide Risk Assessment | 207 Motutara Road, Muriwai</td></tr>
<tr><th>Project number</th><td colspan="7">12612462</td></tr>
<tr><th>File name</th><td colspan="7">12612462- RiskAssess207 Motutara Rd MuriwaiFINAL.docx</td></tr>
<tr><th rowspan="2">Status Code</th><th rowspan="2">Revision</th><th rowspan="2">Author</th><th colspan="2">Reviewer</th><th colspan="3">Approved for issue</th></tr>
<tr><th>Name</th><th>Signature</th><th>Name</th><th>Signature</th><th>Date</th></tr>
<tr><td>S4</td><td>0</td><td>Ryan Hayes</td><td>Don Macfarlane</td><td>D Macfarlane</td><td>Matt Howard</td><td>MHoward</td><td>30/04/2024</td></tr>
<tr><td>[Status code]</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>[Status code]</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>[Status code]</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

GHD Limited
Contact: Matt Howard, Technical Director - Engineering Geology | GHD
27 Napier Street, GHD Centre Level 3
Freemans Bay, Auckland 1010, New Zealand
T +64 9 370 8000 | **F** +64 9 370 8001 | **E** aklmail@ghd.com | **ghd.com**

Contents

Table index

Figure index

Appendices

1. Introduction

1.1 Background

Two significant rainfall events affected the Waitakere area in late January and early February, resulting from the impacts of ex-tropical cyclones Hale and Gabrielle, respectively.

The Cyclone Gabrielle weather event of 14 February 2023 resulted in widespread catastrophic flooding and slope instability in the settlement of Muriwai where several debris avalanches (which included rocks and trees) occurred, some of which turned into saturated debris flows as they travelled downslope. These flows resulted in damage to buildings and infrastructure. Two fatalities occurred due to impact of landslides on private dwellings. This tragic event was similar to a 1965 storm event that also claimed two lives.

Following the February event, rapid building assessment of residential properties was undertaken in Muriwai, with some houses having access by owners restricted (a yellow placard – e.g. access in daylight hours only) and some for which no access was permitted (a red placard).

GHD has been engaged by Auckland Council (AC)[1] to carry out landslide risk assessments and to provide associated landslide risk management advice and geotechnical investigations recommendations in the Waitakere area, specifically for the residential areas of Muriwai, Piha and Karekare. These assessments were necessary due to widespread, damaging landslides associated with Cyclone Gabrielle in February 2023. GHD has completed a landslide risk assessment[2], whereby some properties were identified as having an unacceptably high risk of being impacted by future large landslides.

1.2 Purpose of this report

The residential property at 207 Motutara Road, Muriwai ('the site') has been assessed by GHD as having an acceptable risk from large scale landslides[3] (see the November 2023 report). However, a localised, damaging landslide occurred, and the purpose of this assessment is to carry out a Quantitative Landslide Risk Assessment (QRA) to estimate the risk of Loss of Life to individuals at the property from local landsliding. The outcome of the QRA will be used to inform subsequent property risk categorisation and building placard designation review by AC.

1.3 Scope

The scope of work requested by AC was as follows:

- Review available historical and recent imagery, including LiDAR.
- Review pertinent historical data and GHD work undertaken as part of the wider Muriwai landslide risk assessment reported in GHD (2023).
- Undertake a site engineering geological assessment of landslide hazards at the impacted property.
- Undertake a QRA where landslide hazards have been identified that pose a Loss of Life landslide risk using the Australian Geomechanics Society Practice Note Guidelines for Landslide Risk Management, commonly known as AGS (2007c).
- Deliver report(s) documenting the QRA inputs and outcome.

Specifically excluded are an assessment of property risk, site specific subsurface geotechnical investigations, service inspections, and groundwater monitoring.

This assessment considers geotechnical matters only. There may be other non-geotechnical considerations that affect the final property risk categorisation or placard designation of which GHD are not aware, such as flood risk and structural damage to property.

---

[1] Under Contract CW198379, Master Services Agreement CCCS: CW74240 dated 7/09/2019

[2] Dated 03/11/2023, document file ref 12612462_Overall Report FINALRev0.docx

[3] In the GHD November 2023 report, 'large scale' landslide hazards refers to landslides originating from the main escarpment that typically have a volume of more than about 50 m3 with the potential to cause total or partial collapse of a dwelling.

Identification of options for the mitigation of geotechnical hazards has not been undertaken as part of this study.

Although considered unlikely, GHD reserves the right to amend the opinions, conclusions and recommendations provided within this report, should additional geotechnical information become available.

1.4 Our Approach

GHD have completed a landslide risk assessment for Muriwai which assessed the risk to life of large-scale landslide hazards to inform possible future dwelling hazard designations. The assessment was limited to ‘large scale’ landslide hazards originating from the main escarpment located to the south-east of Muriwai because the initial placard assessment was largely aimed at mitigating risks associated with these.

Smaller, more localised landslide hazards that could originate (or may have already initiated) from other areas in Muriwai such as within the footprint of individual residential properties were not considered in the overall risk assessment. However, these have the potential to cause damage to dwellings and subsequently pose a risk to life for residents, partly due to the relatively steep topography and the potential for high travel velocity.

The approach of identifying landslide hazards over large and common source areas, such as that used for the November 2023 Muriwai assessment, does not capture numerous, smaller scale, localised landslides. For this reason, a QRA is presented for the individual property (207 Motutara Road) based on an assessment that includes site observations and a desktop review of available information. The results aid with informing the QRA with regards to the presence of existing and historical landslide hazards and site-specific slope conditions.

The QRA undertaken for this report only assesses risk to life to occupants of the dwelling due to landsliding. The assessment considers a number of hazard scenarios as follows:

1. the **most likely significant landslide hazard** based on the observed hazards with respect to the mapped landslides and their distribution within the broader landscape. In addition, considerations of the hazard relationship to topography, position on the hillslope and proximity to the elements at risk are also included. This represents a credible hazard scenario following a triggering event with a similar frequency as the February 2023 event.
2. Existing geohazards that have resulted from recent failures with the potential to pose risk to life, such as regression and/or remobilisation of translational failures that are upslope or downslope of a dwelling, or failure of oversteepened fill and cut slopes. These represent hazards that exist at the site and may be triggered by a more frequent event in the range of *certain to almost certain*[4] to occur.
3. Other possible geotechnical slope instability hazards that have potential to pose a risk to life, such as failures of fills, cuttings and failed retaining walls. These represent hazards that may have a range of likelihood from *almost certain to possible*.

The process of risk assessment involves estimation of likelihood, consequence and risks based on available information for the study site. The methodology used for the QRA is outlined in Appendix A. The site-specific input parameters and uncertainties are described in Section 3.

A glossary of terminology is presented in Appendix B.

---

[4] The terminology used when referencing probabilities has been adopted from the Qualitative Measures of Likelihood table for assessing risk to property in AGS (2007c). For this assessment, these terms and associated probabilities are Certain = 0.99, Almost Certain = 0.1, Likely = 0.01, Possible = 0.001, Unlikely = 0.0001, Very Unlikely = >0.00001

2. Site conditions

2.1 Site description

The site is located at 207 Motutara Road, Muriwai, legally described as Lot 1 DP 186496, and has an approximate area of 1535 m^2. A GHD engineering geologist inspected the site on 12 December 2023. No inspection was undertaken within or under the house. However, a video taken by the homeowner that was made available to us by AC provides an insight into some of the interior damage.

As shown in Figure 2.1, the affected property is located towards the northern end of the township on the western, seaward, side of Motutara Road, approximately 40 m south of Muriwai Lodge. In the area surrounding the site, Motutara Road is positioned on a bench feature which separates the approximately 70 m high, steep main escarpment to the east, and a smaller, approximately 20 m high more localised escarpment, with variably shallow to steep slopes to the east. The property spans most of this escarpment from the driveway entrance at approximately 65 m RL to its western extent at approximately 50 m RL. The slopes within the property are generally quite shallow (10-20°).

There is a single, two storey dwelling on the property which appears to have been constructed on a fill platform at approximately 54 m RL. The natural slopes surrounding the dwelling are generally quite shallow (10-20°) with the exception of the slopes beyond the northeast corner of the dwelling which rise up to Motutara Road at a moderate to steep grade (up to 40°).

Numerous ‘large’ landslides (mapped on Figure 2.1) originating from the crest and upper slopes of the main escarpment to the east of the site occurred during Cyclone Gabrielle but did not affect the dwelling, terminating at or close to Motutara Road. A smaller scale, localised failure originating from the slopes below Motutara Road, just outside (to the east) of the property boundary, at approx. 65 m RL impacted the eastern side of the dwelling.

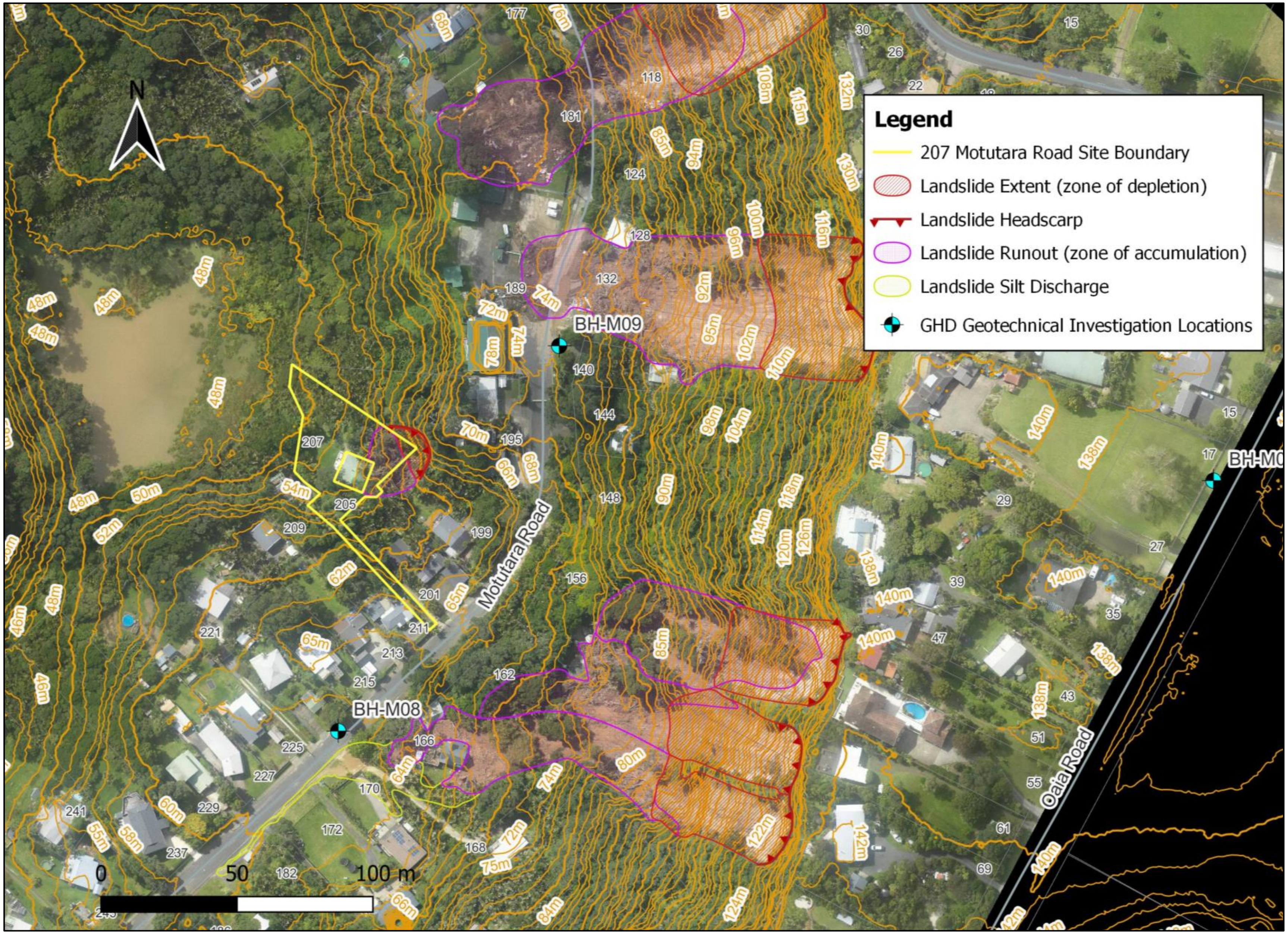


Figure 2.1 *Site location at 207 Motutara Road, Muriwai*

2.2 Site services and sources of water

Auckland Council's GeoMaps presents relevant underground services and hydrologic information for the site. An excerpt of the data is presented in Figure 2.2.

Two overland flow paths are mapped within the property boundary. One, originating outside the boundary on the slopes above the dwelling to the southeast, is mapped flowing beneath the dwelling into an open watercourse northwest of the property. The second flow path originates in the northwest corner of the property and flows into the same open watercourse. Both overland flow paths have a catchment size of approximately 2000 m^2 – 4000 m^2.

The landslide that impacted the dwelling does not appear to directly correlate with either of the mapped overland flow paths (see Figure 2.2).

No underground services associated with water are mapped on the slopes above the dwelling.

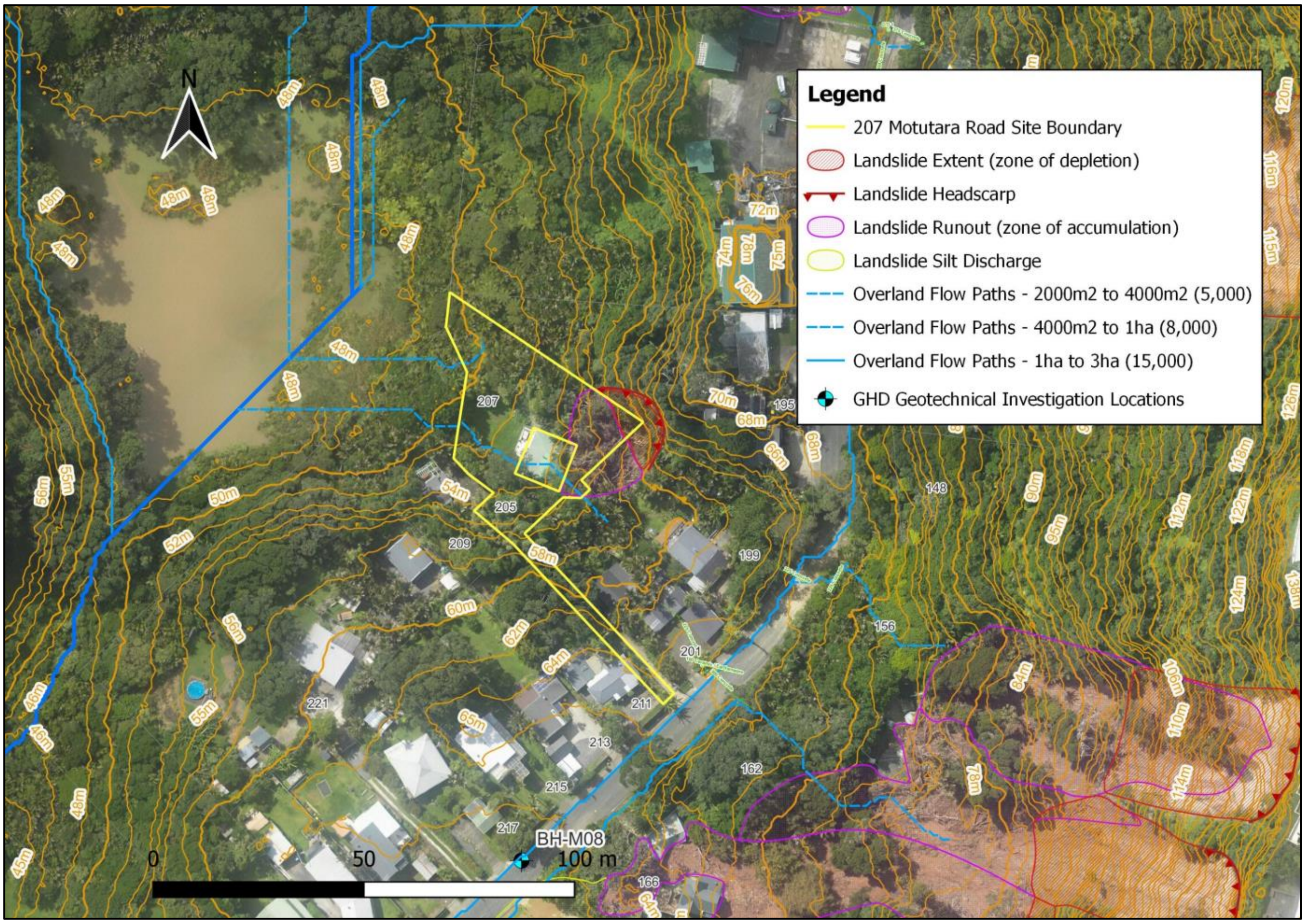


Figure 2.2 Overland flow paths and underground services for the site (source: Auckland Council GeoMaps).

2.3 Published geology

The published 1:50,000 scale geological map of the area (Hayward, 1983) indicates the site is entirely underlain by the Awhitu Sand Formation (qs), part of the Kaihu Group (Figure 2.3). More recently deposited Holocene aged (less than 10 kya) dune sands (qmf) are present at lower elevations, as part of the coastal landscape. These are approximately 100 m west of the property.

Awhitu Sands (‘qs’) are Pliocene aged (less than 2 Mya) characterised as ‘coarse sand, clayey, often limonitised (as laterally discontinuous layers), with minor tuff, lignite and siltstone’ (Hayward, 1983). The formation originated as coastal sand deposits. Awhitu Sands are generally oxidised to an orange-brown colour when exposed at the surface, resulting in a weak iron-cementation that allows for the development of large, more than 50 m high steep slopes, such as the escarpment.

The formation is weakly bedded and cross-bedded at the sub metre scale. Locally the formation is inferred to dip north and eastward at a shallow angle. Occurrences of silty/clayey horizons are occasionally visible in outcrop and have been encountered within boreholes, however it is unclear how persistent they are spatially.

Although not mapped, more recent colluvium material formed as a result of ongoing erosion and periodic landsliding associated with escarpment recession is likely present on the basal/lower slopes of the escarpment.

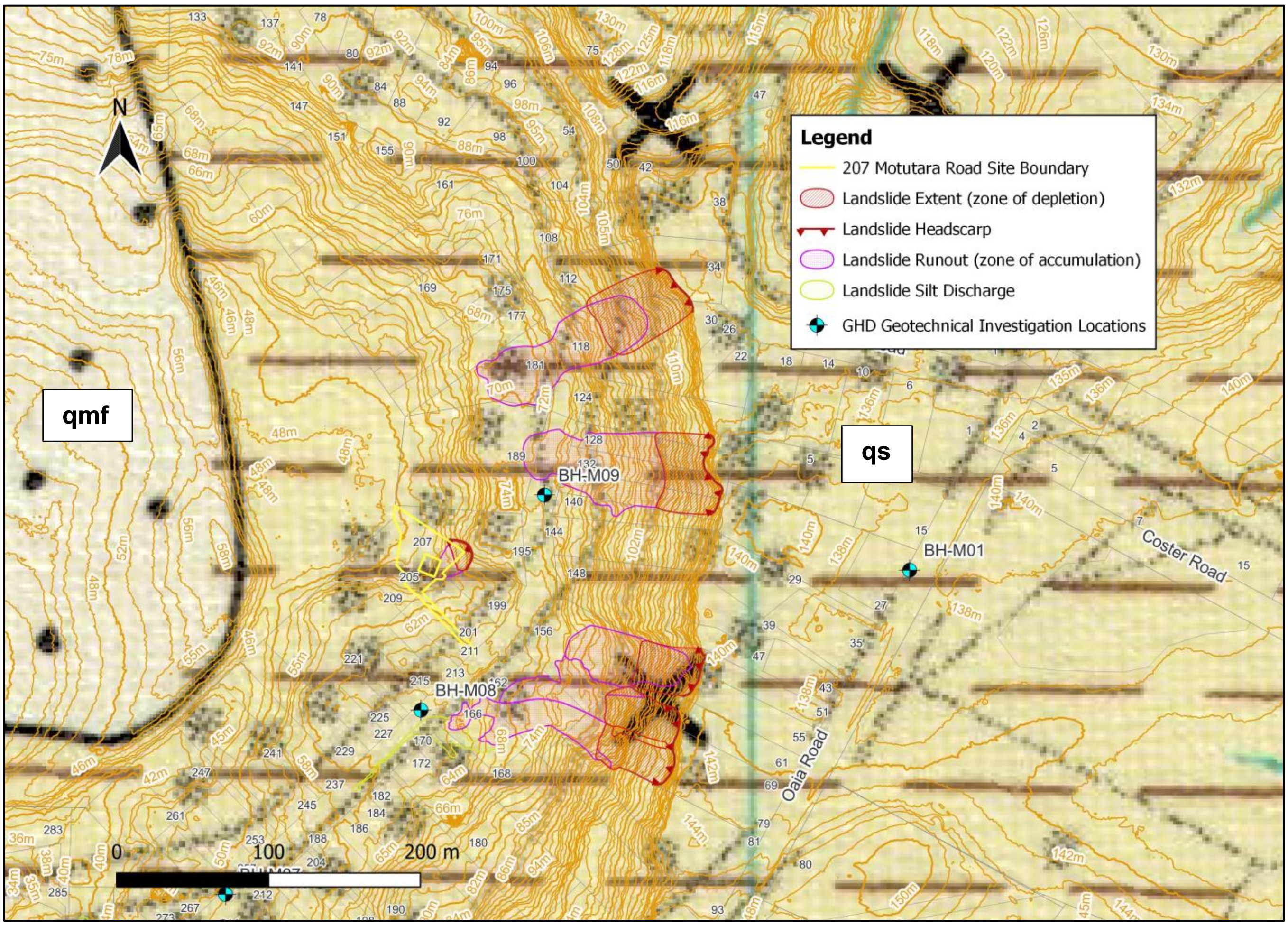


Figure 2.3 ***Excerpt of the Waitākere 1:50,000 scale geological map (Hayward, 1983[5]), illustrating the underlying geology at the site location.***

---

[5] Hayward, B.W. 1983: Sheet Q11, Waitakere. Geological Map of New Zealand 1:50,000 Map

2.4 Historical data summary

A summary of the historical data relevant to 207 Motutara Road is presented in Table 2.1.

Table 2.1 Summary of historical data

	Applicable data available	Notes
Historic aerial photos	- 1940 - 1950 - 1953 - 1975 - 2000 - 2004 - 2008 - 2010-2011 - 2015-2017 - 2022	- No obvious evidence of instability was identified from the historical aerials within the property itself. - Evidence of wider scale erosion evident from 1940, where many of the spurs leading off main escarpment are bare as well as sections of the main escarpment crest. Suggests ongoing erosion of surficial soil. No regression of escarpment observed. - Photos sourced from Retrolens and Auckland Council Geomaps.
NZ Geotechnical database	Two boreholes (BH-MH08 and BH-MH09) completed by GHD in July 2023. Located approx. 50 m south (BH-MH08) and 60 m northeast of property boundary (see Figure 2.1).	- 10.95 m deep boreholes drilled at 63 m RL (BH-MH08) and 72 m RL (BH-MH09). - BH-MH08 entirely within loose to medium dense silty sand interpreted as Paleo Colluvium - BH-MH09 entirely within loose to medium dense silty sand interpreted as Awhitu Sand Formation. A <1 m band of highly weathered, extremely weak sandstone was encountered at 9.6 m
Council GeoMaps	Overland flow data from Auckland City Council ArcGIS.	- Discussed in Section 2.2.
Rapid building Assessment Geotech reporting	N/A	N/A
Independent geotechnical reports	N/A	N/A
Anecdotal information	Landowner video provided in June 2023	Incorporated into Section 2.5
LiDAR Imagery	Feb 2023 Digital Terrain Model.	- Possible historical headscarps in the escarpment suggest ongoing recession through landsliding. - Possible hummocky ground on the natural slopes above the dwelling.

2.5 Engineering geological model

2.5.1 Awhitu Sand Formation

Awhitu Sands are exposed within the entire escarpment and have generally been described as medium dense to very dense sands overlying massive, extremely weak, moderately weathered, iron-cemented fine to coarse sandstone. Irregular layers of clay and silt rich material are typically spaced every 5-10 m and relatively thin (less than 1.0 m and often less than 0.1 m). The strength profile of the Awhitu Sands displays a relatively linear increase with depth.

The in-situ nature of the Awhitu Sands suggests they are relatively permeable. However, as discussed in the November report there is also significant evidence for perched groundwater tables shown by:

- Multiple occurrences of groundwater seeps or springs emerging within the middle and base of the escarpment slope face, from above underlying (presumed aquiclude) layers of clay and silt rich beds as well as heavily oxidised iron pans
- Variable and sharply changing weathering profile with localised layers of cemented iron oxidised sand between un-oxidised material at depth.

2.5.2 General landslide characteristics

As described in the November report (GHD 2023), the landslides identified across Muriwai following the February 2023 event can be categorised into two types based on their physical characteristics as follows:

Large slips: typical headscarp widths of 30-70 m, with source and debris runout areas more than 100 m in length, often extending well past the base of the escarpment onto the flatter slopes below, and

Smaller isolated slips: generally with headscarp widths of less than 30 m and extending less than 50 m. As a result, debris from these landslides generally did not reach the base of the escarpment.

2.5.3 Landslide impacting the site

The landslide that impacted the dwelling at 207 Motutara Road is illustrated by site mapping on Figure 2.4 and is also shown in the context of different imagery on Figure 2.5 and Figure 2.6 below. An interpretive cross section through the site is presented in Figure 2.11. Ground conditions have been interpreted from a combination of historical data, site mapping and nearby geotechnical investigation data. The cross section is indicative only and may not be representative of actual conditions.

The landslide headscarp (Figure 2.7) has an approximate width of 15 m and is at an elevation approximately 15 m above the rear of the dwelling, near the crest of the localised escarpment below the topographic bench feature on which Motutara Road is located. Following a high degree of ground saturation, it initiated on a 30-40° vegetated slope as a ~ 1-2 m deep translational (with a possible rotational component) failure. The exposed headscarp has left a steeper 45-55° slope profile.

The landslide does not appear to have developed into a debris flow similar to failures seen elsewhere in Muriwai, likely due to its relatively short travel distance. A large volume (potentially up to 300 m^3) of landslide debris was deposited at the base of the slope, with a maximum thickness of approximately 2 m impacting the rear of the dwelling (Figure 2.8 and 2.9). A significant portion of the damage to the rear wall of the dwelling was caused by the entrainment of large trees within the debris (Figure 2.9). No building collapse as a result of landslide damage was noted.

Ponding of water on the body of the landslide (Figure 2.9) as well along its lateral extents has occurred following the event and a video provided by the homeowner indicates that water seepage and secondary silt discharge has entered the ground floor of the dwelling. This likely occurred during subsequent relatively frequent rainfall events as a consequence of poor drainage conditions. Figure 2.10 shows landslide debris did not flow around the sides or front of the house.

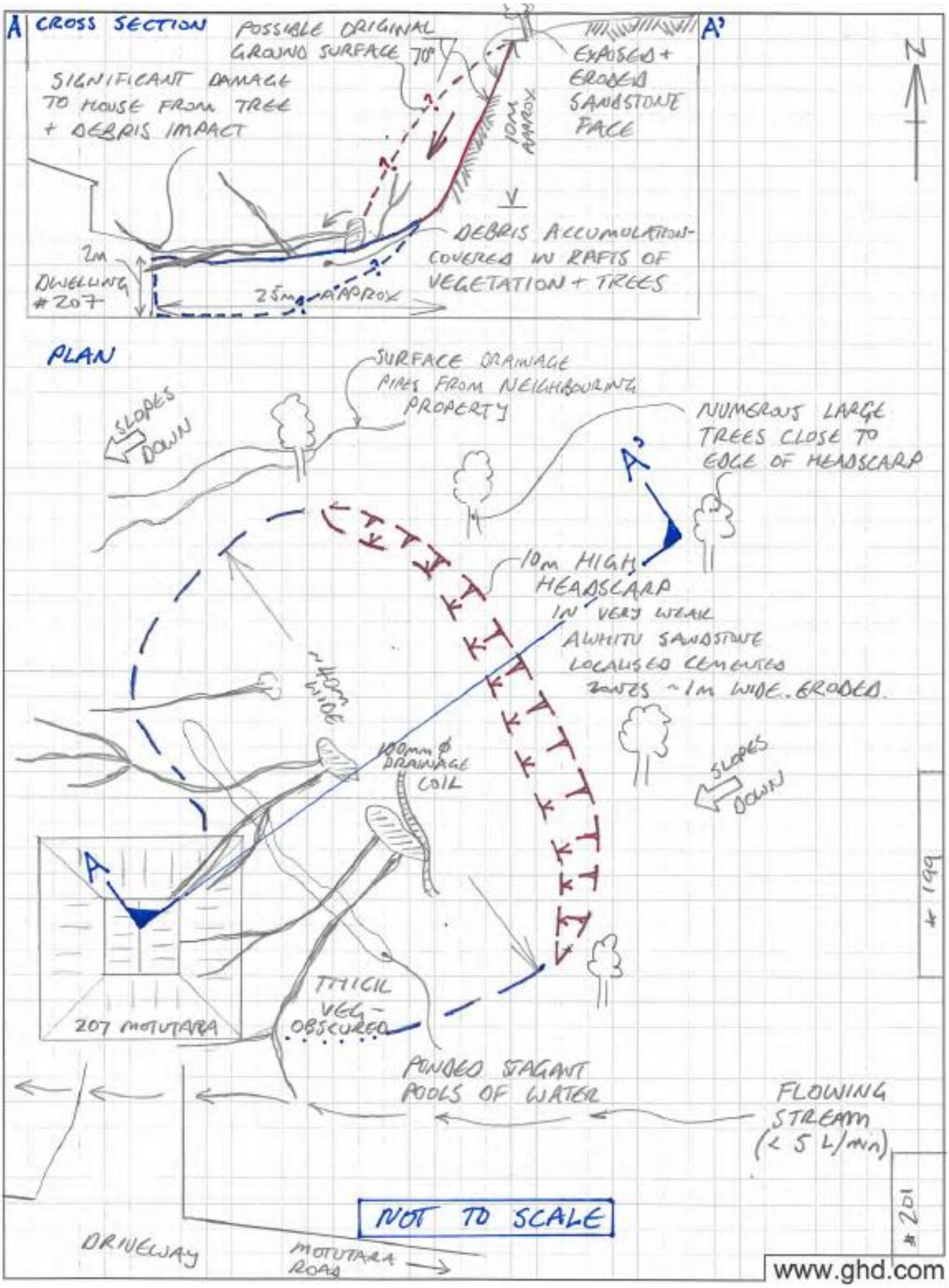


Figure 2.4 *GHD site mapping of the landslide (completed 12 December 2023)*

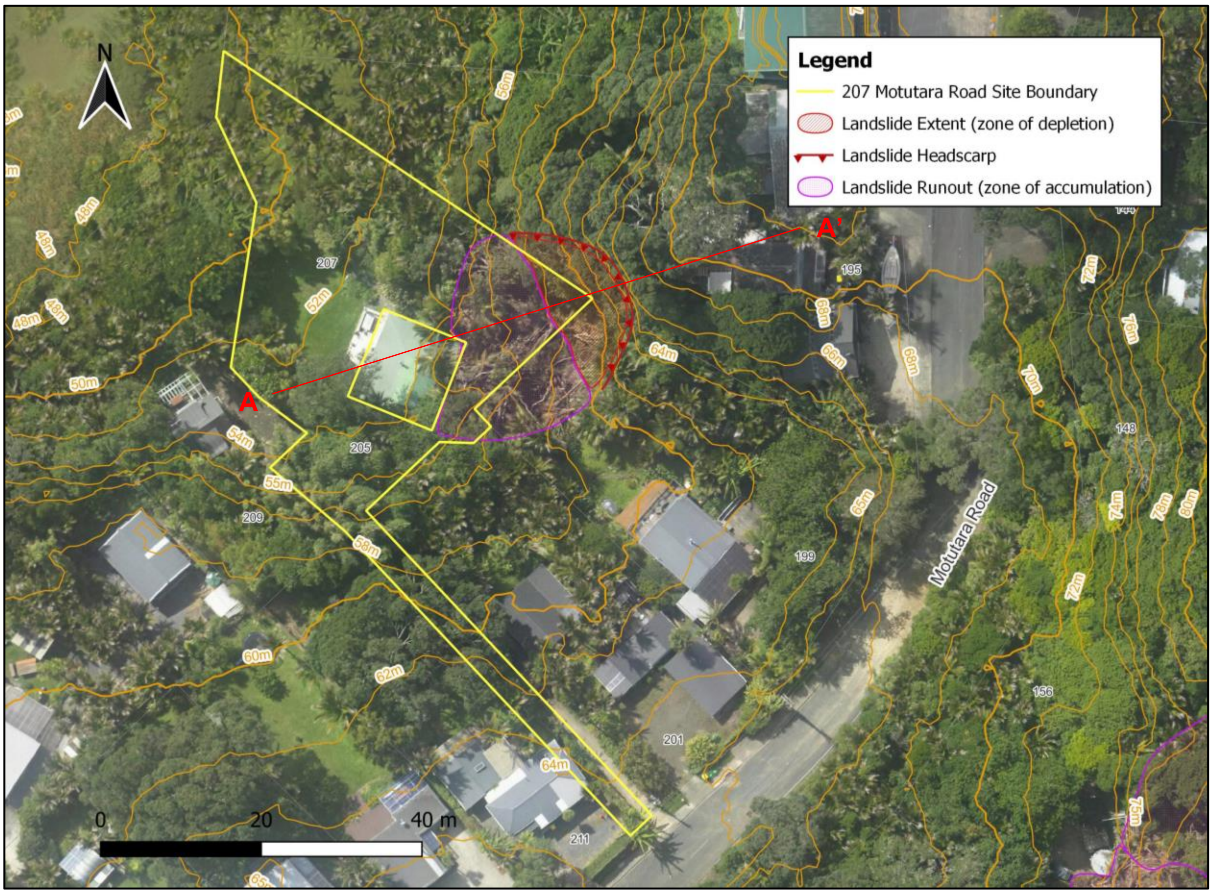


Figure 2.5 *Landslide location relative to the site shown on February 2023 aerial image.*

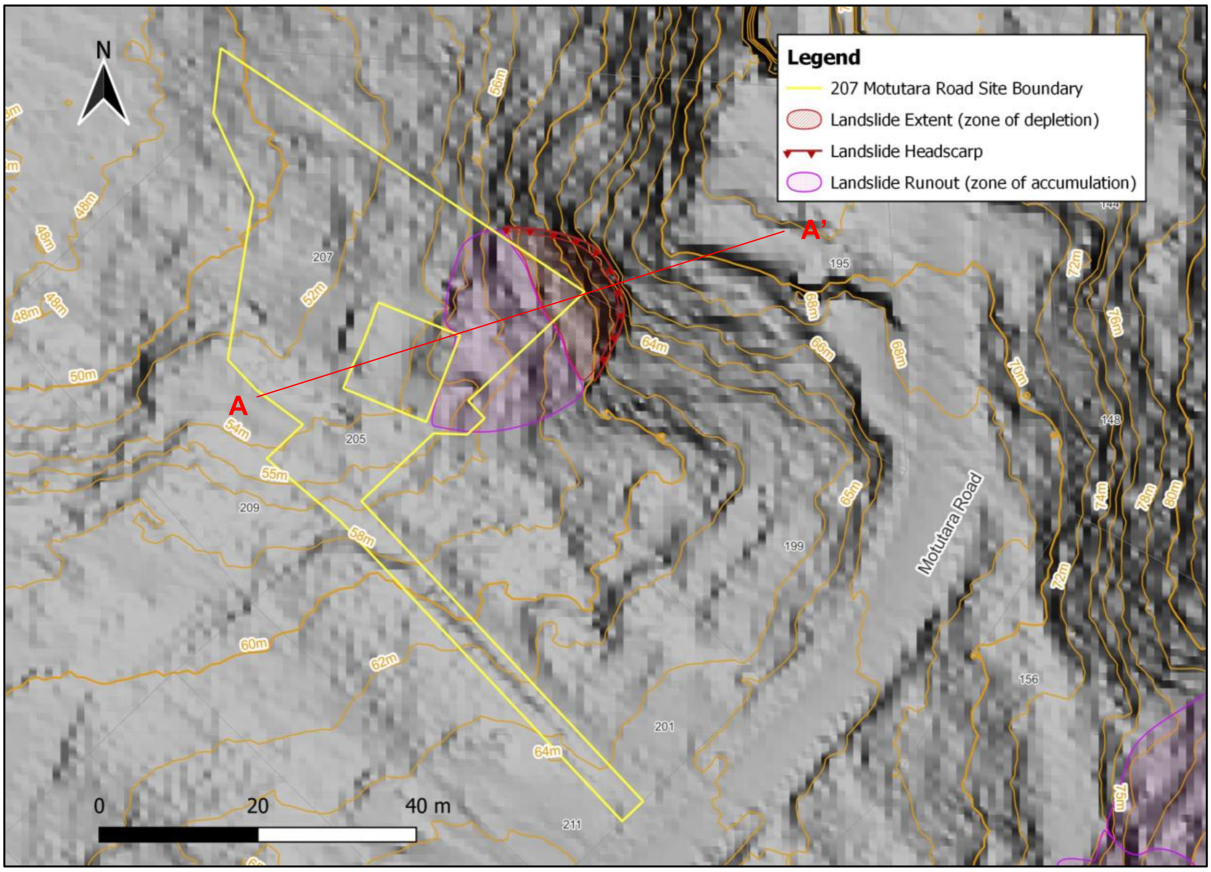


Figure 2.6 *Landslide location relative to the site shown on LiDAR Hillshade (source: Auckland Council Feb 2023).*

Figure 2.7 Awhitu Sand Formation in the exposed landslide headscarp.

Figure 2.8 Close to the lateral extent of the landslide debris at the rear of the dwelling, looking southwest.

Figure 2.9 Ponding of water on top of the landslide debris at the rear of the dwelling, looking west.

Figure 2.10 Relatively flat area in front of the dwelling, looking east.

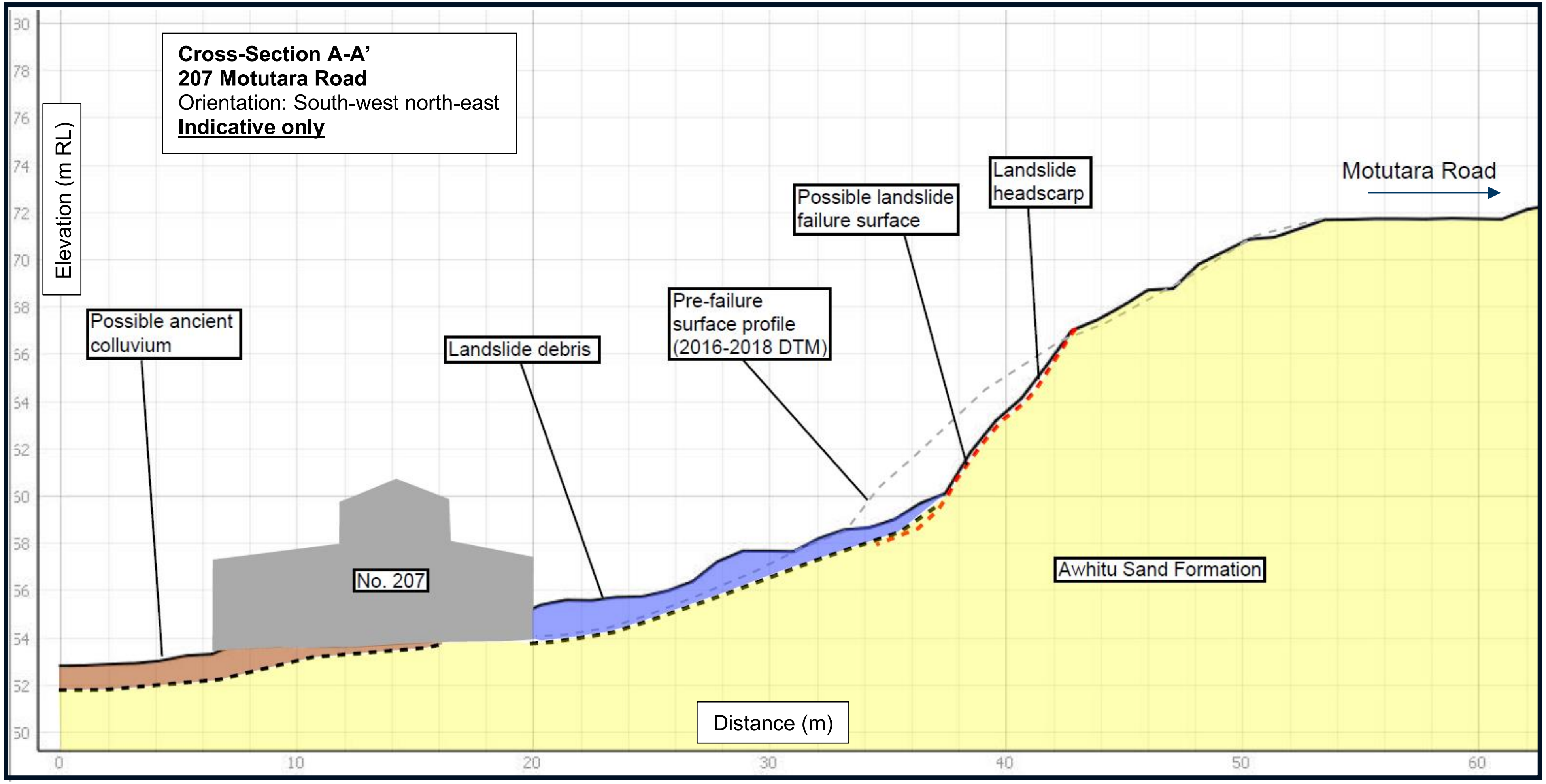


Figure 2.11 *Indicative interpreted geological cross section through the site at 207 Motutara Road.*

3. Landslide risk estimation

The Australian Geomechanics Society Landslide Risk Management guidelines, published in 2007 and now commonly referred to as AGS (2007), have been adopted for the following unmitigated loss of life landslide risk assessment. Appendix A provides background information and guidance on how the methodology has been applied for assessing risk to life at the site.

The existing dwelling (or a new dwelling of similar construction occupying the same location) has been considered as the element at risk for this assessment. Our assessment assumes the recent landslide debris has been removed. Where appropriate, sensitivity checks have been undertaken for comparative purposes.

3.1 Hazard characterisation

The landslide hazards considered as part of this assessment are as follows:

- **LS1** (Landslide Hazard 1) – The most likely future landslide to occur on the slopes above the property. The landslide would be a shallow failure, likely occurring on the slope along the existing headscarp on the crest of the escarpment and potentially having a volume in the order of 150 m^3. The assumed landslide characteristics have been inferred from observations of the previous failure and landslides to occur elsewhere in Muriwai. The possible source area considered for a future landslide above the dwelling is highlighted on Figure 3.1 and Figure 3.2 below.
- **LS2** (Landslide Hazard 2) – Regression of the existing landslide headscarp. This is likely to have a volume somewhat smaller than the landslide that occurred in February 2023.

3.2 Likelihood of landsliding ($P_{(H)}$)

The basis for estimating probability of occurrence for each landslide hazard considered as part of this assessment is provided in Appendix A and the probabilities adopted are presented below.

3.2.1 Likelihood of LS1

Two considerations of probability for occurrence for the most likely future landslide are:

- $P_{(H'1)}$ is the probability that the rainfall threshold for the most likely significant landslide is exceeded, which is taken as a proxy for landslide initiation. This is assumed to be 1 in 100 or **0.01** (see analysis by AC in Appendix A) or 1 in 50 or **0.02** under the influence of future climate change.
- $P_{(H'2)}$ is the probability that a slope above the dwellings fails. Given the current condition of the slope above the dwelling, it is conservatively considered almost certain to certain that the most likely future landslide would occur directly above the dwelling. A value of $P_{(H'2)}$ **= 0.5** has been adopted.

3.2.2 Likelihood of LS2

Given the current condition of the exposed landslide headscarp (greater than 45° and comprising Awhitu Sands), it is considered that regression of the existing landslide will occur at the same location during a relatively frequent rainfall event. A value of $P_{(H'1)}$ of **1 in 10** or **0.1** is adopted whilst $P_{(H'2)}$ is considered certain and a value of **1.0** is adopted.

3.3 Probability of spatial impact ($P_{(S:H)}$)

Our estimate of spatial probability is based on several factors which depend on the landslide hazards being considered and site-specific slope conditions. Our approach is detailed in Appendix A. Figure 3.1 and Figure 3.2

below provide an indication of the slope conditions at 207 Motutara Road and the surrounding area (slope angles and inferred preferential flow paths, respectively).

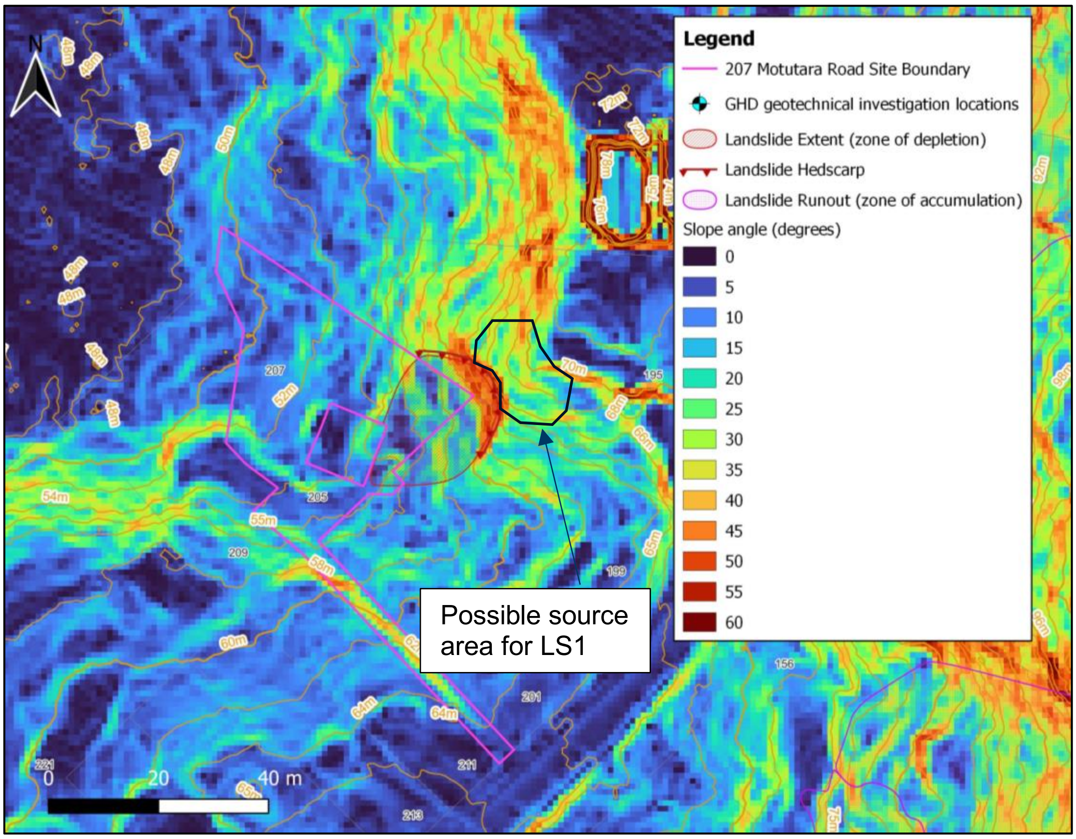


Figure 3.1 ***Slope map of 207 Motutara Road and surrounding area. Slope angles based on 2023 DTM data.***

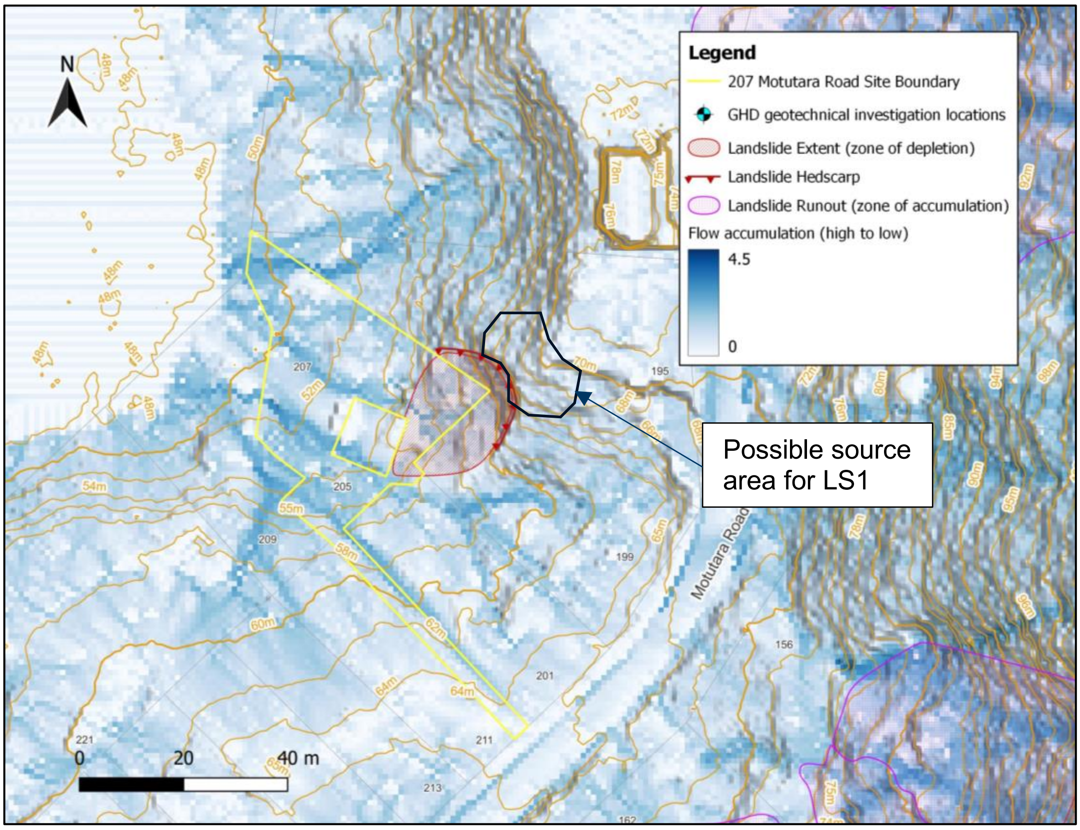


Figure 3.2 ***Flow accumulation map of 207 Motutara Road and surrounding area. Indicates preferential flow path for surface water. Modelling based on 2023 DTM data.***

3.3.1 Probability of spatial impact (LS1)

Two conditional factors are considered for the most likely significant landslide:

- $P_{(S':H'1)}$ is the probability that if the landslide occurs it travels in the direction of (towards) the dwelling. Based on the position of the dwelling at the base of a relatively planar slope exhibiting a somewhat convex geomorphology at its crest, a landslide initiating in the possible source area above the site (Figure 3.1) would likely travel downslope (southwest) towards the dwelling. Based on the flow accumulation plot (Figure 3.2) a landslide is unlikely to take a preferential flow path. A value of **1.0** is adopted.
- $P_{(S':H'2)}$ is the probability that if the landslide occurs it will reach the dwelling. The natural slopes above are generally steep (30-40°). Based on an approximate landslide volume of 150 m^3, an adopted travel angle of 33° (Appendix A methodology based on data from Piha and Karekare) would project the landslide to within 5 m of the rear of the dwelling. Empirical methods in the GHD (2023) Muriwai risk assessment report indicate that, based on an average downslope angle of approximately 35°, the predicted travel distance angle would be approximately 30° (for confined and partly confined travel paths. *Note: LS1 would have an unconfined travel path*). This value also generally agrees with published data in Hunter & Fell (2002). This would project the landslide to the rear of the dwelling. A probability value of **0.5** has been adopted.

3.3.2 Probability of spatial impact (LS2)

Landslide hazard LS2 involves upslope or lateral regression of the existing landslide.

- If the existing landslide hazard were to reactivate and result in regression of the headscarp, it is likely that the new landslide would follow the same path as the previous one, and hence travel towards the rear of the dwelling. As such a probability of **1.0** has been adopted for $P_{(S':H'1)}$.
- Regression of the existing landslide is expected to result in mobilisation of a somewhat smaller volume of debris. Given the observed behaviour of the previous slide (impacting the rear of the dwelling) and the topography of the site, any future failure is judged certain to almost certain to reach the dwelling. As such, a value of **0.8** is adopted for $P_{(S':H'2)}$.

3.4 Temporal spatial probability ($P_{(T:S)}$)

As discussed in Appendix A, a temporal spatial probability of **0.68** is the adopted value for each property and has been used in this assessment.

3.5 Vulnerability ($V_{(D:T)}$)

In the event the future most likely landslide reaches the dwelling from the slopes above, the depth of the debris is likely to be in the order of 1-2 m and result in a similar level of damage as the previous landslide (impact the rear of the dwelling but not result in building collapse or significant inundation). The entrainment of vegetation including large trees has the potential to increase the vulnerability. Therefore, a value **0.05** is adopted for LS1.

In the event that regression of the existing landslide occurs on the slope above the dwelling, it is expected that debris with a somewhat smaller volume than previously would strike the rear of the dwelling but not result in building collapse. Based on the vulnerability table in Appendix A, a value of **0.01** is adopted for LS2.

3.6 Unmitigated Risk Estimation

A summary of the risk estimation for each conceivable landslide hazard is presented in Table 3.1 below. A sensitivity check assuming a higher probability of occurrence for $P_{(H)}$ is included for comparative purposes.

We acknowledge that assessing risk has an inherent degree of uncertainty and may only be accurate to within half an order of magnitude. This level of uncertainty would not change the outcome of the analysis. Refer to Appendix for further discussion.

Table 3.1 Summary of unmitigated risk estimation for each hazard type.

Hazard	Annual probability of the landslide $P_{(H)} = P_{(H'1)}$ x $P_{(H'2)}$	Spatial probability $P_{(S:H)} = P_{s':H'1)}$ x $P_{(S':H'2)}$	Temporal probability $P_{(T:S)}$	Vulnerability $V_{(D:T)}$	Risk $R_{(LOL)}$	Risk evaluation*
LS1 ***(most likely future landslide hazard)***	**0.01 x 0.5**	**1.0 x 0.5**	**0.68**	**0.05**	**8.5 x 10^{-5}**	**Tolerable**
LS1 *Sensitivity check*	*0.02 x 0.5*	*1.0 x 0.5*	*0.68*	*0.05*	*1.7 x 10^{-4}*	*Not tolerable*
LS2 ***(regression of existing landslide hazard)***	**0.1 x 1.0**	**1.0 x 0.8**	**0.68**	**0.01**	**5.4 x 10^{-4}**	**Not tolerable**
LS2 *Sensitivity check*	*0.2 x 1.0*	*1.0 x 0.8*	*0.68*	*0.01*	*1.1 x 10^{-3}*	*Not tolerable*

**The evaluation is a guide only based on recommendations from AGS (2007) which provides a suggested tolerable Loss of Life Risk for the person most at risk.*

4. Conclusion and recommendation

This report has presented the results of a quantitative risk assessment for unmitigated loss of life in relation the property located at 207 Motutara Road, Muriwai, Waitākere. Two landslide hazards (LS1 and LS2) have formed the basis of this assessment.

Assessment of the most likely future landslide (LS1) estimates the annual risk to loss of life for the person most at risk to be approximately **8.5 x 10^{-5}**. This risk is tolerable based on the AGS (2007c) suggested tolerable Loss of Life Risk for the person most at risk (see Appendix A). Our estimate suggests a higher frequency event as a result of climate change could result in a risk marginally higher than the AGS (2007c) suggested tolerable Loss of Life Risk for the person most at risk.

Assessment of further (future) failure of the existing landslide hazard (LS2) estimates the annual risk to loss of life for the person most at risk to be approximately **5.4 x 10^{-4}**. This risk is higher than the AGS (2007c) suggested tolerable Loss of Life Risk for the person most at risk (see Appendix A).

Potential remedial measures to lower the risk level from the existing landslide hazard (LS2) may be possible. However, identifying such measures is outside of the scope of this study.

As discussed above, this report considers geotechnical matters only. There may be other non-geotechnical considerations that affect final placard designation of which GHD are not aware, such as flood risk and structural damage to property.

We understand AC are currently reviewing their tolerable and acceptable risk criteria for risks associated with landsliding. We recommend Council review the risk assessment presented in this report against the AC risk criteria to assess whether it is appropriate to assess the property risk categorisation and remove or re-assess the current placard designation for the site.

5. Limitations

This report has been prepared by GHD for Auckland Council and may only be used and relied on by Auckland Council for the purpose agreed between GHD and Auckland Council as set out in section 1.2 of this report.

GHD otherwise disclaims responsibility to any person other than Auckland Council arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

The opinions, conclusions and any recommendations in this report are based on assumptions made by GHD described in this report (refer section 1.2 of this report). GHD disclaims liability arising from any of these assumptions being incorrect.

An understanding of the geotechnical site conditions depends on the integration of many pieces of information, some regional, some site specific, some structure specific and some experienced based. Hence this report should not be altered, amended, abbreviated, or issued in part in any way without prior written approval by GHD. GHD does not accept liability in connection with the issuing of an unapproved or modified version of this report.

Verification of the geotechnical assumptions and/or model is an integral part of the design process - investigation, construction verification, and performance monitoring. If the revealed ground or groundwater conditions vary from those assumed or described in this report the matter should be referred back to GHD.

This risk assessment does not mean that there will be no further landsliding impacting this property or group of properties.

Appendix A

AGS (2007) Background

1. Overview

This appendix document outlines the methods and procedures used to estimate risks to loss of life for the person-most-at-risk at the site described in the covering report. This document should be read in conjunction with the covering report as it contains information not presented in the covering report. This document should not be separated from the main report.

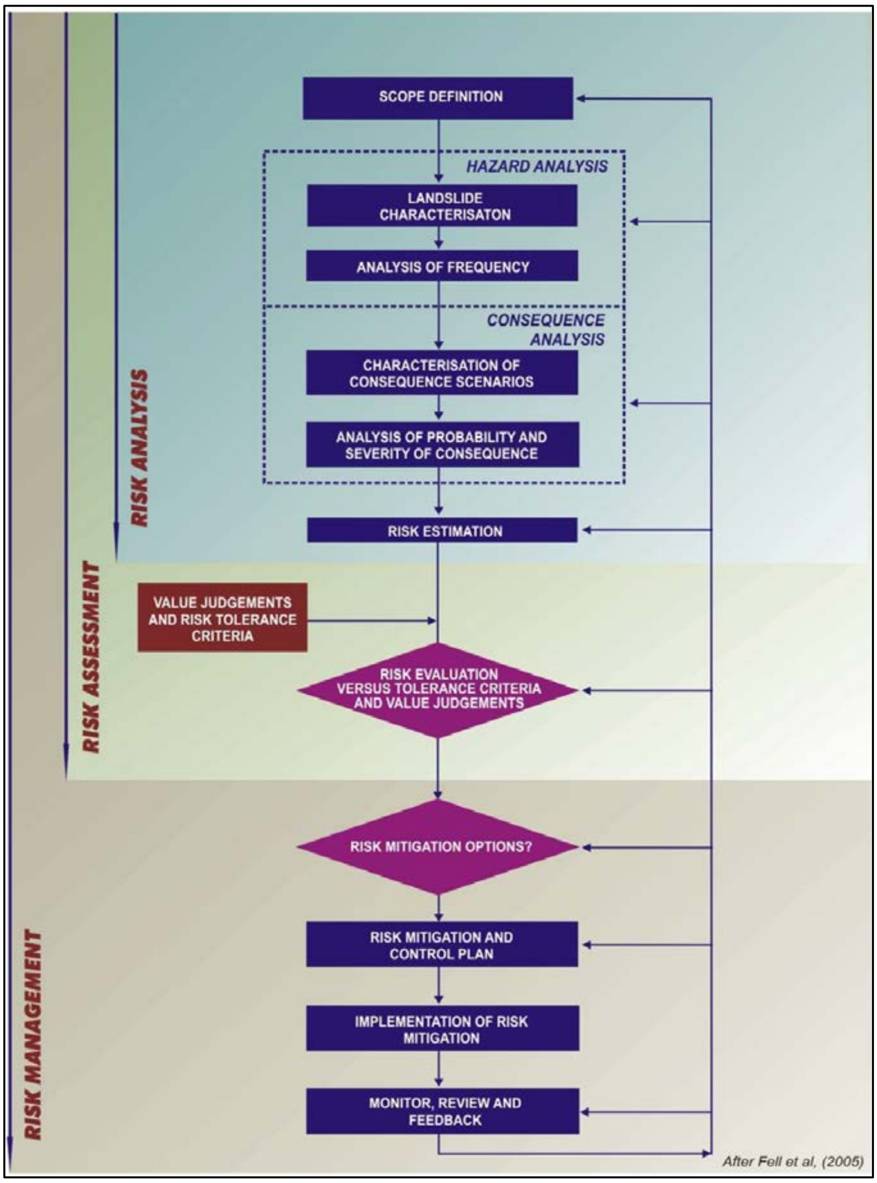
2. Landslide Risk Management Framework

2.1 Background

The 1998 Thredbo landslide, in which 18 persons were killed, highlighted the challenges faced from building upon steep slopes and led to the development of the Australian Geomechanics Society Landslide Risk Management guidelines, published in 2007 and now commonly referred to as AGS (2007). The suite of guidelines is recognised nationally (Australia) and internationally as world-leading practice. The reader of this report is encouraged to consult the freely available LRM resources which can be accessed at: https://landsliderisk.org/.

The ”Practice Note Guidelines for Landslide Risk Management” (AGS 2007c), provide technical guidance in relation to the processes and tasks undertaken by geotechnical practitioners who prepare LRM reports including appropriate methods and techniques. The Practice Note is a statement of what constitutes good practice by a competent practitioner for LRM, including defensible and up to date methodologies and provides guidance on the quality of assessment and reporting, including the outcomes to be achieved and how they are to be achieved.

The framework for landslide risk management is presented in the figure below and represents a framework widely used internationally.



After Fell et al, (2005)

Figure A1 Framework for landslide risk management.

2.2 Risk Estimation Methodology

AGS (2007c) requires risks to loss of life to be estimated quantitatively for the person-most-at-risk. The person-most-at-risk will often but not always be the person with the greatest spatial temporal probability (i.e. the person most exposed to the risk). The Individual Risk-to-Life is defined as the risk of fatality or injury to any identifiable (named) individual who lives within the zone impacted by the landslide; or who follows a particular pattern of life that might subject him or her to the consequences of the landslide. The risk of ‘loss-of-life’ to an individual is calculated from:

$$\mathbf{R}_{(LoL)} = \mathbf{P}_{(H)} \times \mathbf{P}_{(S:H)} \times \mathbf{P}_{(T:S)} \times \mathbf{V}_{(D:T)}$$

Where:

$\mathbf{R}_{(LoL)}$ is the risk (annual probability of death of an individual).

$\mathbf{P}_{(H)}$ is the annual probability of the landslide (event).

$\mathbf{P}_{(S:H)}$ is the probability of spatial impact of the event impacting an individual taking into account the travel distance and travel direction given the event. For example, the probability of an individual in a building or in the open being impacted by a rockfall / landslide at a given location.

$P_{(T:S)}$ is the temporal spatial probability (e.g. of the building or location being occupied by the individual at the time of impact) given the spatial impact and allowing for the possibility of evacuation given there is warning of the event occurrence.

$V_{(D:T)}$ is the vulnerability of the individual (probability of loss of life of the individual given the impact).

2.3 Landslide Risk Assessment Uncertainty

The process of risk assessment involves estimation of likelihood, consequence and risks based on available information for the study site. By its very nature, much of the data, including historical and current inventories may be incomplete whilst an understanding of the triggering events has a degree of uncertainty attached to it. Judgement is required to estimate the nature and size of potential hazards, their frequency of occurrence and their impact on a variety of elements at risk. As these judgements are based on the knowledge, experience and understanding of the assessor, it is not unusual for different assessors to make different judgements about the level of risk.

The thought process used in establishing likelihoods, consequences and determining spatial and temporal factors for properties has been documented for transparency. The structure of the risk assessment process is well defined and values for some input parameters have been tabulated to guide standard approaches by different assessors. However, this should not be mistaken for precision given the limitations of the inputs outlined above. Generally, the levels of likelihoods and risks should be thought of as being within a range of typically +/- half an order of magnitude.

While the basis for the judgements contained in this report are well documented, and the levels of risk considered to be good representations of reality, the accuracy and precision of the process should not be overestimated and should always be used in an appropriate manner in combination with risk management including mitigation and treatment options.

3. Hazard Characterisation

AGS (2007c) generally states that all credible hazards originating on, above and below the sites should be assessed. This is generally a predictive exercise based on knowledge and understanding of the geological and geomorphological setting with a view to assembling historical evidence for past hazard events.

3.1 Defining the Most Likely Significant Landslide

Following Cyclone Gabrielle, small landslides within the Muriwai area were often noted to be shallow translational slides developed in the upper residual profile of the Awhitu Sand Formation which, under saturation, transition into debris flows. Detailed analysis by GHD of the mapped landslides within the Karekare and Piha areas, which included size, estimated volume, travel distance and travel angle, was undertaken to characterise the nature and distribution of landslides following the rainfall events that occurred in early 2023, particularly the Cyclone Gabrielle rainfall event, has been used as a basis for defining the magnitude of the ‘most significant landslide’ for the site.

A total of 80 landslides were mapped throughout Karekare and Piha following the storm events in Jan and Feb 2023. These landslides were then grouped into categories of volume in 50 m^3 increments. Results for an assessment of “frequency as categorised by volume” is shown in Figure 1 below.

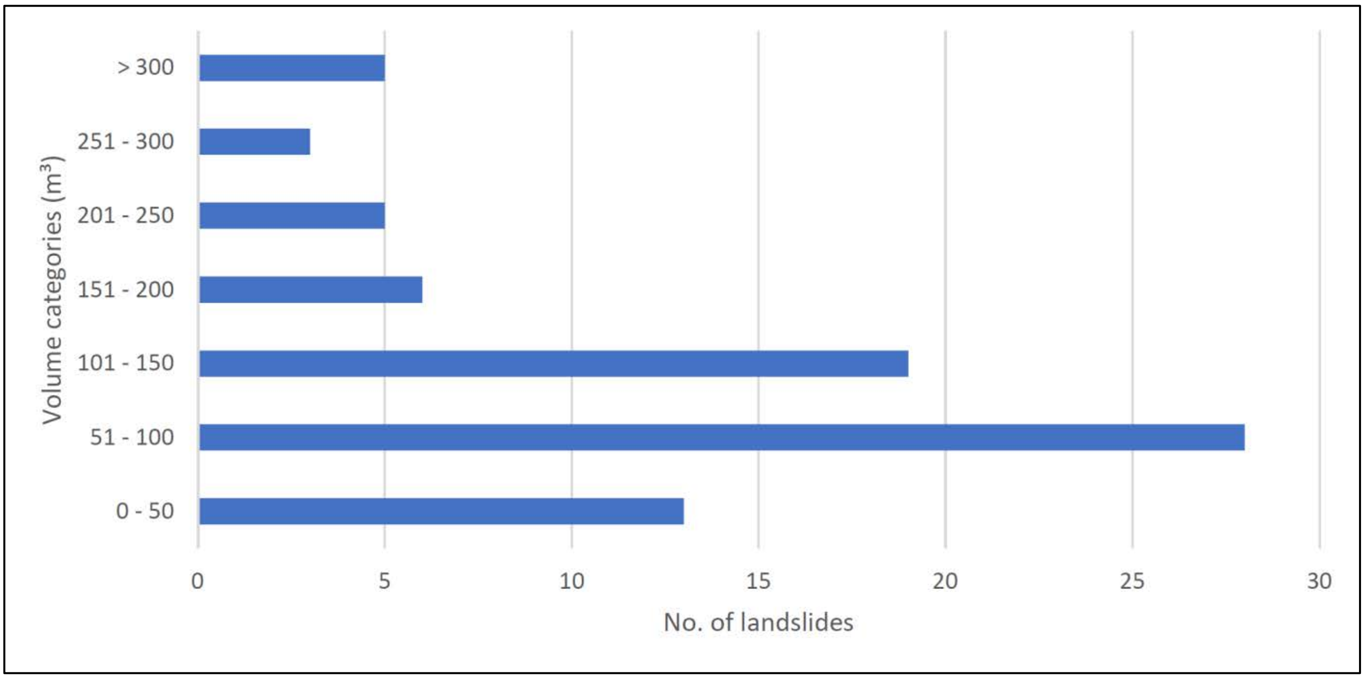


Figure A2 *The number or frequency of mapped debris flows (on the x axis) as categorised by volume increments for mapped source areas of debris flows (on the y axis in m^3) in Karekare and Piha.*

In addition, detailed information regarding volume size, travel angle, travel distance, confinement (either unconfined or channelized) and the degree of damage caused by slides impacting dwellings and building was also collated and a number of additional graphs were developed as below:

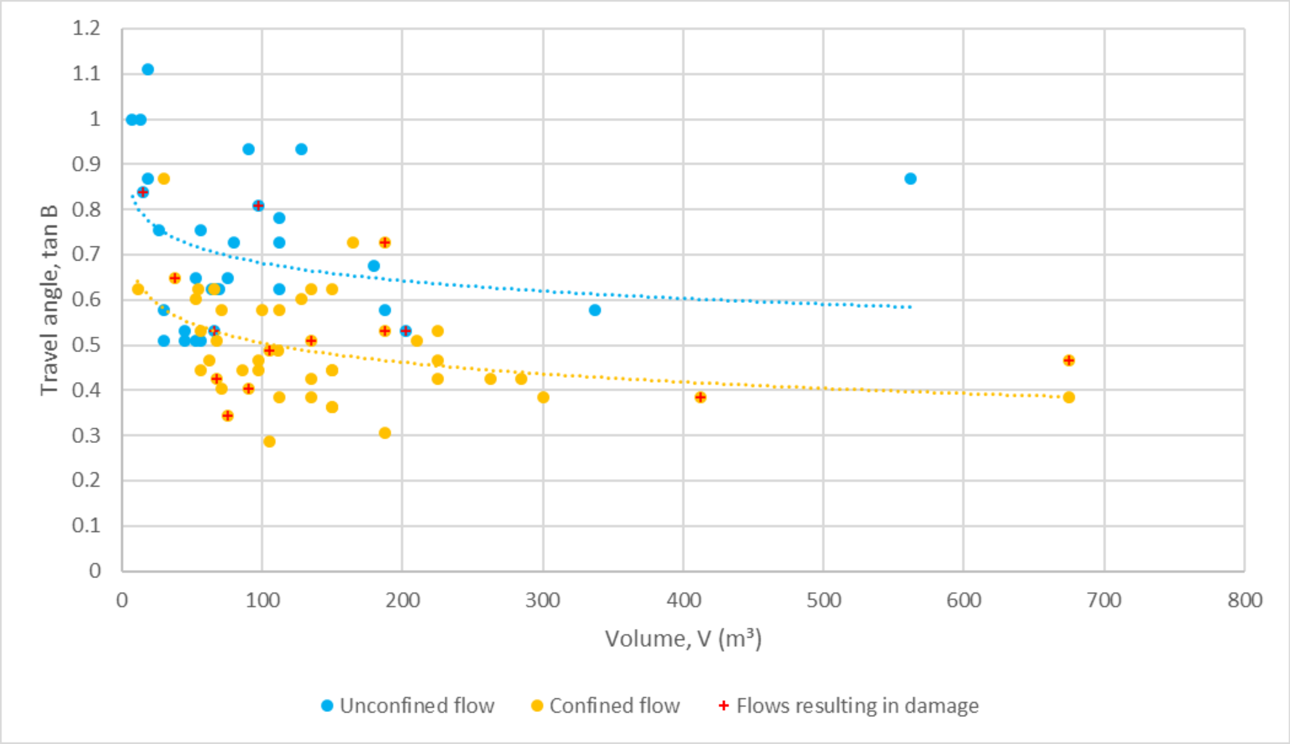


Figure A3 *Travel angle vs volume of source area for the Karekare and Piha debris flows*

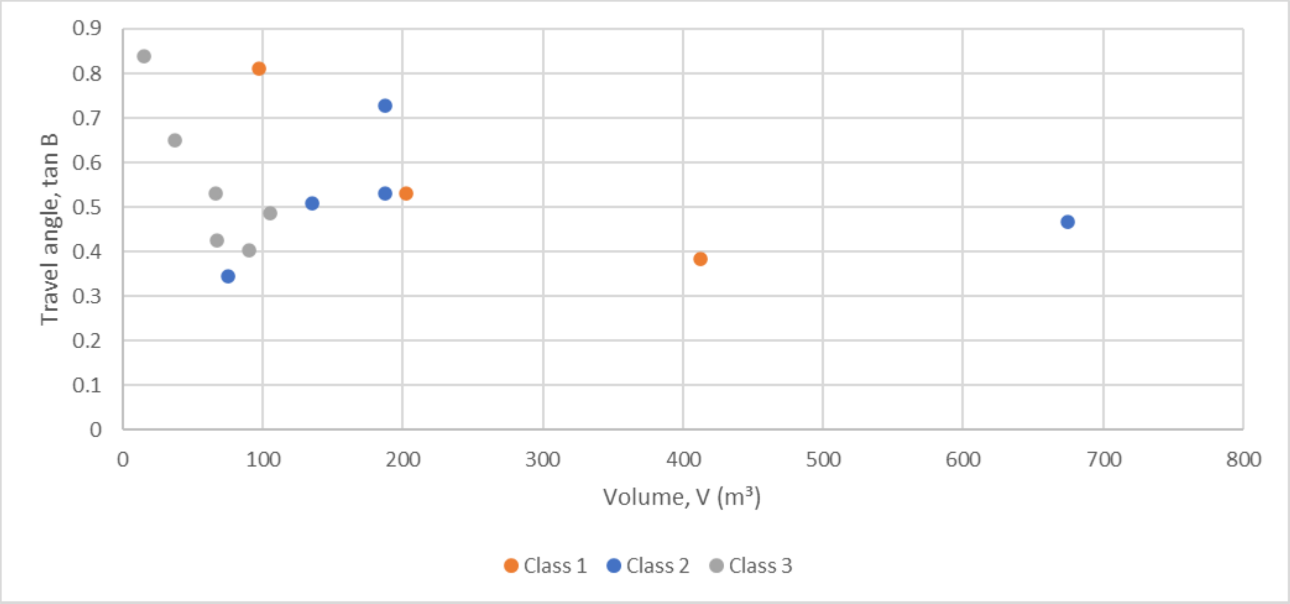


Figure A4 ***Plot of only those debris flows known to have caused some degree of damage to dwellings and buildings. Note Class 1 = Complete destruction/collapse of building, Class 2 = Partial destruction/collapse of building, significant inundation and Class 3 = Limited damage to building but no collapse or inundation, damage is other property infrastructure e.g., access stairs.***

This assessment highlights a number of important points relating the nature of these hazards including:

- Whilst a range of volumes of source areas for debris flow was noted, the most common or likely sized event was of the order of 50-100 m^3 as determined by the frequency plot.
- Many smaller volume source areas for debris flows (less than 75 m^3) typically only caused some lesser damage to buildings but once the volume increased above 100 m^3, then the vast majority of debris flows were noted to have caused partial or full collapse of dwellings and buildings.
- The greater the volume of the source area, the lower the travel angle and the greater the runout or travel distance.
- Unconfined debris flows generally have a higher travel angle compared to confined or channelized debris flows of the same volume. This means that confined or channelised debris flows have a longer runout or travel distance and hence have more potential to impact elements at risk further down the slope.

Based on this site-specific data and analysis, GHD has adopted a working definition for these risk assessments of what is termed the **most likely significant landslide** as follows:

- The volume of most likely significant landslides is assumed to be 100 $m^{3.}$
- This volume has been shown to cause significant building damage resulting in partial to full dwelling and building collapse.
- As a result, this hazard is considered to have a high probability for causing loss of life.
- Where this hazard is unconfined, the adopted travel angle based on Figure 3 has been taken as Tan (B) = 0.69 or approx. = 35°
- Where this hazard is confined or channelised the adopted travel angle based on Figure 3 has been taken as Tan (B) = 0.50 or approx. = 26.5°
- Comparison with Figure 6 from Hunter and Fell (2002) suggests the site derived travel angles are generally consistent with other data presented in that plot.

The definition of the **most likely significant landslide** is considered to be a reasonably conservative but not overly cautious estimate of the potential hazard that may affect the site. This is based on an assessment of an overview of landslides that GHD has observed in Muriwai, Karekare and Piha in 2023.

It is noted however that in some specific circumstances, larger recent debris flows may have occurred in close proximity to the site under investigation. As such, where there is evidence for a larger hazard, the assessor may

choose to adopt a larger volume event based on judgement and knowledge of that particular site. In this case other values for travel angle can be read from Figure 3.

IMPORTANT NOTE: It is duly acknowledged that volume alone does not necessarily account for the full potential of a debris flow to cause significant damage and other factors such as the degree of channelization, the additional entrainment of volume within a channel, the degree of saturation of the debris materials, the location of the source area on the hillslope, the direction of travel, the distance of travel and the velocity of the hazard at the point of impact all play important roles in the destructive capacity of any debris flow. Some of these factors are considered within the risk assessment process as conditional probabilities in spatial considerations.

3.2 Description of Other Landslide Types

As discussed in the scope of the covering report, other landslide hazards may exist at the site under assessment. These may include existing geohazards that have resulted from recent failures with the potential to pose risk to life in the immediate short-term (i.e. within the next few years) such as regression of translational failures to occur downslope of dwelling, failure of over-steepened fill and cut slopes, rockfall hazards associated with exposed rock faces/headscarps and/or loose debris remaining upslope of dwellings.

In addition, other possible geotechnical slope instability hazards relating to modified slopes (i.e. human made) may also exist and have potential to pose a risk to life - such as failures of fills, cuttings and failed retaining walls. This represents hazards that may have a range of likelihood from almost certain to possible.

Where appropriate, descriptions and definitions for each of these hazards are provided in the covering report on a case-by-case basis and will be specific to the observed hazard and actual conditions at this site.

3.3 General Descriptors for Size Classification of Landslides.

Generalized or relative descriptions of size classification systems for landslides vary significantly depending on the country of origin and the nature of the landslide hazards typically encountered. For the purposes of these assessments, GHD proposes to use the following size classification descriptions adopted from the Transport for New South Wales (TfNSW) Guide to Slope Risk Analysis Version 4 (TfNSW 2014) (see Table 3.1 below).

Table A3.1 Landslide size classification

Relative size term	Volume range	Typical mid-range dimensions (width x length x depth in metres)
Very small	<20 m3	4 x 4 x 0.5
Small	20 to 200 m3	10 x 10 x1
Medium	200 to 2000 m3	20 x 20 x 2.5
Large	2000 to 20000 m3	40 x 40 x 5
Very large	>20,000 m3	60 x 60 x 8

4. Likelihood $P_{(H)}$

Likelihood or annual probability of occurrence of the landslide, $P_{(H)}$, is one of the most critical but difficult to estimate factors as part of the risk assessment process.

4.1 The Most Likely Significant Landslide

The recent flood / storm events, the estimation of recurrence intervals for that event and the occurrence of the observed hazards form the basis for the current estimated probability of occurrence for the most likely significant landslide hazard. However, observations of the recent events noted that not all similar slopes failed as a result of

the initiating storm event and as such, an additional consideration for probability of occurrence has been included within the analysis by using conditional probabilities as follows:

$$P_{(H)} = P_{(H'1)} \times P_{(H'2)}$$

Where:

$P_{(H'1)}$ = Probability that the rainfall threshold for the most credible significant landslide is exceeded which is taken as a proxy for landslide initiation. This is assumed to be 1 in 100 or 0.01 (see analysis and discussion by Auckland Council below) or 1 in 50 or 0.02 under the influence of future climate change.

$P_{(H'2)}$ =Probability that the slope for the specific assessment fails, which relates to how many of the actual slopes failed out of the total number of all slopes present. This probability is typically based a on spatial analysis of the total area of failed landslides slopes compared to the total area of all slopes for the geomorphic setting in which the site is located.

4.2 Auckland Council Guidance on Frequency for Most Likely Significant Landslide

Council provided GHD with an assessment of available rainfall data associated with Cyclone Gabrielle (Auckland Council 2023) (AC memo). During Cyclone Gabrielle, the tipping bucket rain gauge at Muriwai failed and was inundated by flood waters. The AC memo also provided rainfall analysis using AC’s Quantitative Precipitation Estimate (QPE) Rain Radar System, which is a real-time rainfall product that utilises the MetService radar. The rainfall data presented by AC indicates a peak rainfall total for Muriwai during the event of 146.9mm, occurring over 12-hour period. This total is >100-year event at a 12-hour duration. The data suggests that for the 12-hour duration rainfall, the Annual Recurrence Interval (ARI) is >100 years and may be in the order of 250 years. However, we understand that the calculation above the 100-year assessment becomes increasingly unreliable, primarily as a result of the relatively short statistical rainfall records available in New Zealand. For the other durations modelled, the rainfall was below the 100-year event.

The AC memo recommended that an envelope of “risk” is estimated as the ARI figures will change over time and as these events are incorporated into the statistical record. The AC memo states that in general, it is considered reasonable to consider the Cyclone Gabrielle event to be in the range of 100-250 year ARI. For this assessment we have assumed that the annual likelihood of a landslide event occurring that is similar in magnitude to the February 2023 event, is about 1 in 100 (i.e., 0.01). This is considered to have a *likely* probability of occurrence.

The assumption of 1 in 100 based on rainfall frequency is a simplifying and possibly conservative assumption that we consider reasonable. It does not consider other factors that could potentially affect stability (antecedent conditions, geology, groundwater conditions, slope height and angle, vegetation, surface water management-overland flow path, overflow from water storage tanks, effect of effluent disposal field), all of which are difficult to quantify.

The AC memo further recommended that risk assessment reports consider the potential for climate change to increase the frequency of high intensity rainfall. We understand that the National Institute of Water and Atmospheric Research (NIWA) has projected a 20% increase in rainfall intensity over the next 100 years which suggests that a 250-year ARI event could increase to a 50-year ARI event. Consequently, we have also included a sensitivity check based on a 50-year ARI event.

We draw the reader’s attention to Section 3 of this report and reiterate that AGS (2007c) generally states that all credible hazards originating on, above and below the sites should be assessed. This report has conformed to this requirement and assessed landslide hazards that were observable during the site mapping and/or able to be interpreted via other means such as readily available aerial photographs, lidar data etc. It should be recognised that specific hazards such as rockfalls, failed retaining walls, over-steepened cuts/fill batters may have likelihoods in the *Certain to Almost Certain* range and are more likely to occur in the short term.

4.3 Other Landslide Hazards

Where other slope failures and instabilities as described in Section 3.2 are considered, individual assessments of $P_{(H)}$, the probability of occurrence, are made on the basis of expert judgment, performance of similar landslides in the area and recent site observations.

When considering hazards that may pose immediate or short-term risks to life it is probable that such hazards will have high likelihoods of occurrence that could be triggered by relatively frequent events. As a result, such hazard may have likelihoods in the *Certain to Almost Certain* range as per the ASGS2007 qualitative descriptors for likelihood.

5. Probability of Spatial Impact $P_{(S:H)}$

The AGS definition of spatial probability is represented by single term $P_{(S:H)}$ and is described as the probability of spatial impact by the landslide on the element at risk, given the landslide occurs and taking into account the travel distance and travel direction.

5.1 The Most Likely Significant Landslide - Upslope of Site

A number of conditional factors may be involved in the spatial distribution for the most likely significant landslide, and for further transparency, the following methodology has been adopted:

$$P_{(S:H)} = P_{(S':H'1)} \text{ x } P_{(S':H'2)}$$

Where:

- $P_{(S':H'1)}$ = The probability that if the landslide occurs it travels in the direction of the site under assessment. If the slopes above are consistent, and planar then probability is assumed to be 0.8 to 1.0 depending on the topography; if the originating landslide enters a channel that is directed onto the property then probability is assumed to be 1.0, or if the landslide enters a channel that is directed away from the sites then the probability is assumed to be 0.05 taking account of a small probability that the landslide may super elevate and leave the channel.
- $P_{(S':H'2)}$ = The Probability that if the landslide occurs it will travel to at least the site under assessment and will impact the property. This is to be based on two considerations as follows:

    1. Modelled Behaviour based on travel distance analysis undertaken by GHD for 80 observed landslides slides in the Karekare and Piha areas (see Figure A3). Either probability = 1.0 if the travel angle projects past the dwelling, = 0.5 if the travel angle projects to the rear of the dwelling or = 0.0 if the travel angle falls short of the dwelling.

And/or

2. Observational behaviour: based on site observations of whether the previous landslides within close proximity to the study site, travelled sufficient distance to reach the site under assessment; if yes Probability = 1.0, if no, then probability = 0

- NOTE 1: The GHD analysis of travel distance highlights the effect of channelisation which shows confined debris flows travel further (i.e., they have a lower travel angle) than those which are unconfined on consistent or planar slopes. Such considerations are included on a site-by-site basis. Interestingly, this event-specific analysis also generally agrees with findings presented in Hunter and Fell (2002).
- NOTE 2: Where significant debris flows have occurred in close proximity to the site under assessment, and the observed travel distance is greater than that estimated using the modelled approach, the preferred GHD approach is to use the greater of the two travel distances to assess spatial impact.

5.2 The Most Likely Significant Landslide – Under the Dwelling/Building and/or Downslope Below the Dwelling/Building

Based on the possible failure area:

- If the failure area is > ~5 m from the dwelling then the value for $P_{(S:H)}$ will be 0 as a landslide occurring at that location will not impact dwelling. (The general assumption is that the landslide headscarp would have a length of 5m based on size of most likely significant landslide).
- If the failure area is within ~5m from the dwelling (like above) then the value for $P_{(S:H)}$ will be 0.5 to account for uncertainty of it encroaching within the footprint of the dwelling.
- If the failure area encompasses a significant portion of the dwelling then the value for $P_{(S:H)}$ will be 1.0 as there is a certain probability it will impact the dwelling.

Estimates of how far back the most significant landslide will regress are difficult to model without a detailed slope stability analysis and sufficiently accurate soil and rock inputs. This would require an intrusive geotechnical investigation which is outside the scope of this study.

GHD has adopted a more empirical approach that assesses the spatial extent of lateral downslope movement of the most likely significant landslide based on direct observations of existing landslides in close proximity to the site under assessment. In the absence of other information, a similar extent of regression has been applied to any future slides. An estimate of $P_{(S:H)}$ can then be made as to the potential interaction with the element at risk.

5.3 Other landslides – Upslope of the study site

Other types of potential landslides situated above dwellings and buildings on the site under assessment, should be assessed in a similar manner to the most likely significant landslide. Estimates of travel distance are taken from Hunter and Fell (2002) and/or previous local knowledge and/or observation of similar landslides in the area.

When undertaking short term assessments, hazards involving reactivation of existing landslides that are located upslope of the study site that didn’t previously reach the site must be taken account. In addition, remobilisation of debris from any upslope landslides must also be assessed for their potential of runout or travel distance using Hunter and Fell (2002).

Similarly potential failures of modified slopes such as cuttings or fills located above or directly adjacent to dwellings and buildings must also be assessed for their spatial impact and the methods of assessment follow the same approach.

5.4 Other landslides – under buildings and downslope of the building

A similar approach to that taken for other landslides upslope has been adopted. Observation of existing failures and how much lateral downslope movement can be used as a proxy for what may occur in the future under a regression type scenario.

5.5 Temporal Spatial Probability $P_{(T:H)}$

These risk assessments have not considered specific occupancy scenarios for each individual residence. We acknowledge that the occupancy of each residence could vary significantly depending on the demographics of the residents and the usage of the residence. For example, some residences may be predominantly used as holiday accommodation, occupied mainly on weekends, whereas other residences could be permanently occupied by working families.

This assessment has assumed the following occupancies:

- Residences are typically occupied for 15 hours each day during weekdays;
- On weekends, residences are occupied for about 20 hours each day;

– The percentage of time a residence is occupied is therefore about 68%.

Any further delineation of the spatial variations in occupancy (i.e. if a bedroom is at the front or the rear of the house etc) are not considered feasible or warranted within the context of the precision of this assessment.

6. Vulnerability $V_{(D:T)}$

6.1 Most likely significant Landslide

AGS (2007c) includes a table of vulnerability values for various inundation and building damage scenarios as adapted by Finlay et al (1999). It is important to note that the AGS (2007c) vulnerability table doesn't adequately cater for all the building damage scenarios GHD has observed in Muriwai, Karekare and Piha. GHD has therefore further adapted this table and combined it with information from the TfNSW Guide to Slope Risk Analysis (2014) as well as observations of damage to buildings and structures resulting from the recent landslides in Muriwai, Karekare and Piha.

The table of vulnerability values used in this assessment is presented in Table A6.1. These values have been used as a guide and expert judgement has been applied to select a value within the range of values where appropriate on a site-specific basis.

Table A6.1 Summary of Vulnerability Values adopted

Case	Range	Typical value to be used in this assessment	Comments
Person in a building that collapses under impact from debris flow	0.8 -1.0	0.9	Death is almost certain. Evacuation unlikely to occur
If building is inundated with debris and the person is buried	0.8 -1.0	0.8	Very high potential for death Evacuation unlikely to occur
If building is inundated with debris but no collapse occurs and the person is not buried	0.01 -0.1	0.1	High chance of survival Evacuation unlikely to occur
If the debris strikes the building only	0.001-0.05	0.01	Very high chance of survival
If failure occurs below the building and results in significant collapse	0.5-0.8	0.6	Moderate to high potential for death. No forewarning signs with evacuation unlikely to occur.
If failure occurs below the building and results in partial collapse	0.01 -0.1	0.05	High chance of survival. Signs of building distress should provide occupants with opportunity to take evasive action.
If failure occurs below the building and results in damage. No collapse occurs.	0.001-0.05	0.005	Very high chance of survival. Evacuation almost certain.

7. Risk Evaluation

The main objectives of risk evaluation are usually to compare the assessed risk to risk levels that are acceptable or tolerable to the community, and therefore to decide whether to accept, tolerate or treat the risks and to set

priorities for remediation. The Tolerable Risk Criteria are usually imposed by the regulator, unless agreed otherwise with the owner/client. AGS (2007d) provides discussion and gives the AGS recommendations in relation to tolerable risk for loss of life. These are summarized in the table below.

Table A7.1 AGS Suggested Tolerable loss of life individual risk.

Situation	Suggested Tolerable Loss of Life Risk for the person most at risk
Existing Slope / Existing Development	10^{-4} per annum (1E-4 pa) or 1 in 10,000 pa
New Constructed Slope / New Development / Existing Landslide	10^{-5} per annum (1E-5 pa) or 1 in 100,000 pa

It is important to distinguish between "acceptable risks" and "tolerable risks". AGS (2007c) states that tolerable risks are risks within a range that society can live with so as to secure certain benefits. It is a range of risk regarded as non-negligible and needing to be kept under review and reduced further if practicable. Acceptable risks are risks which everyone affected is prepared to accept. Acceptable risks are usually considered to be one order of magnitude lower than the Tolerable risks.

8. References

Auckland Council (2023). 'Guidelines on the use of AGS (2007) for landslide risk assessment in Auckland following the 2023 flooding and cyclone'. Memorandum dated 20 September 2023.

Australian Geomechanics Vol 42 No 1 March 2007 Extract "Practice Note Guidelines for Landslide Risk Management 200" AGS (2007c)

P J Finlay, G R Mostyn & R Fell (1999). 'Landslides: Prediction of Travel Distance and Guidelines for Vulnerability of Persons'. Proc 8th. Australia New Zealand Conference on Geomechanics, Hobart. Australian Geomechanics Society, ISBN 1 86445 0029, Vol 1, pp.105-113.

Hunter. G., & Fell. R. (2002).' Estimation of Travel Distance for Landslides in Soil Slopes'. Australian Geomechanics, Vol 37, No2.

New South Wales Government, Transport for New South Wales 'Guide to Slope Risk Analysis' Version 4, April 2014.

Appendix B

Glossary of Terms

DEFINITION OF TERMS

Acceptable Risk – A risk which, for the purposes of life or work, society is prepared to accept as it is with no regard to its management. Society does not generally consider expenditure in further reducing such risks justifiable~~.~~

Authority or **Council** having statutory responsibility for community activities, community safety and development approval or management of development within its defined area/region

Consequence – The outcomes or potential outcomes arising from the occurrence of a landslide expressed qualitatively or quantitatively, in terms of loss, disadvantage or gain, damage, injury or loss of life.

Creep Failure – A time-dependant deformation mechanism where constant stress is applied to a material. Creep failure can be identified by ridges the ground surface and curved tree trunks.

Dropout – A landslide feature occurring along the length of the road-side on the downslope edge. Drop outs can result in the undermining the road carriageway.

Elements at Risk – The population, buildings and engineering works, economic activities, public services utilities, infrastructure and environmental features in the area potentially affected by landslides.

Entrainment – The process of surface sediment transportation through water and mass movement.

Frequency – A measure of likelihood expressed as the number of occurrences of an event in a given time. See also Likelihood and Probability of Occurrence.

Hazard – A condition with the potential for causing an undesirable consequence. The description of landslide hazard should include the location, volume (or area), classification and velocity of the potential landslides and any resultant detached material, and the probability of their occurrence within a given period of time.

Individual Risk to Life – The risk of fatality or injury to any identifiable (named) individual who lives within the zone impacted by the landslide or who follows a particular pattern of life that might subject him or her to the consequences of the landslide**.**

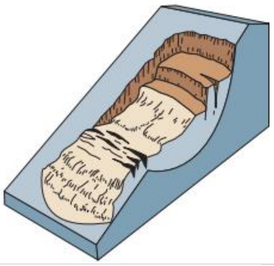
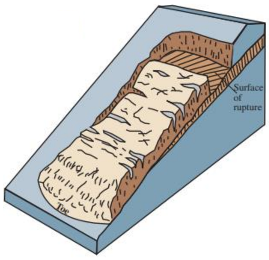
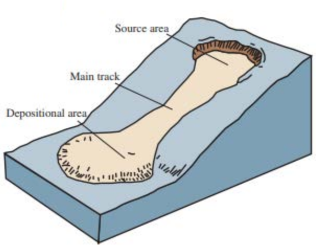
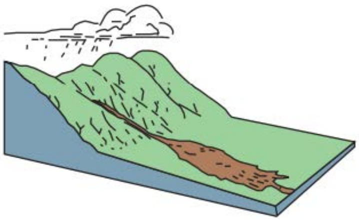
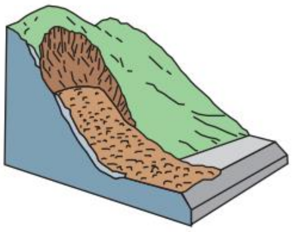
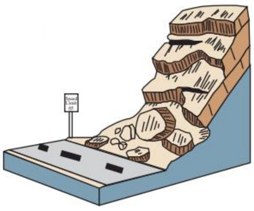
Landslide - A landslide is defined as the movement of a mass of rock, debris, or earth down a slope. The most widely used landslide classification system is that proposed by Cruden and Varnes in 1996 (after Varnes 1954 and Varnes 1978). This has been updated by Hungr, et al., 2014. In its most simple form two nouns are used to describe, firstly the type of material involved and secondly, the mechanism of failure, i.e., rock fall, debris flow.

Landslide inventory – An inventory of the location, classification, volume, activity and date of occurrence of landsliding

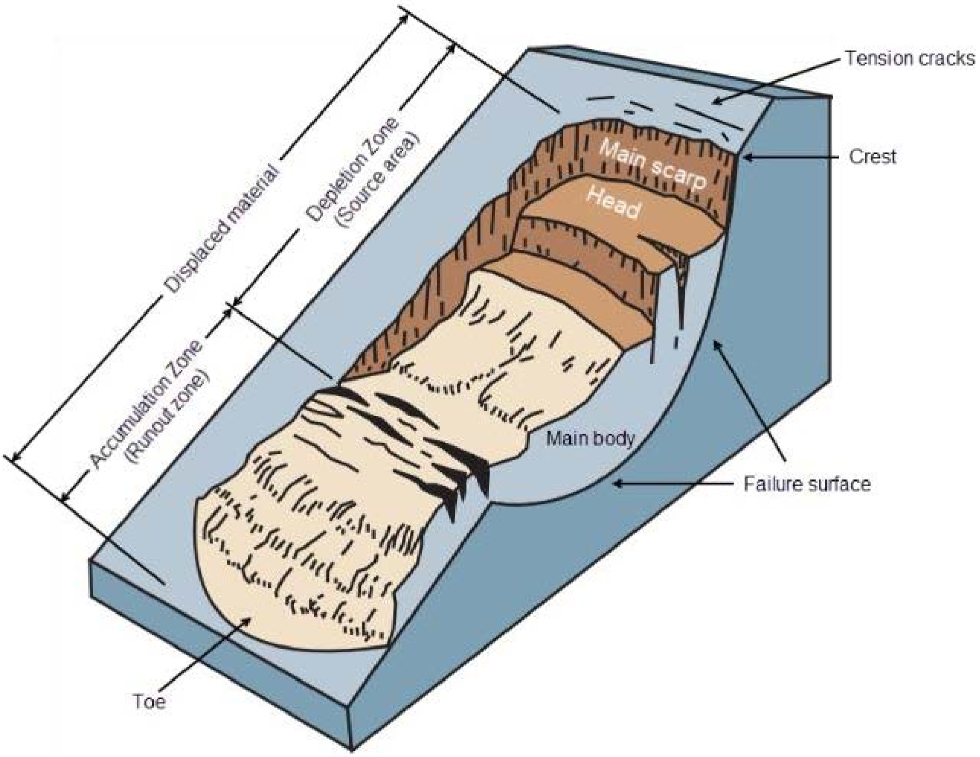
Landslide Risk - Landslide risk is defined herein as the likelihood that a particular landslide will occur and the possible consequences to a specific element at risk (property or human life) taking account of both spatial and temporal considerations.

Landslide Susceptibility – A quantitative or qualitative assessment of the classification, volume (or area) and spatial distribution of landslides which exist or potentially may occur in an area. Susceptibility may also include a description of the velocity and intensity of the existing or potential landsliding.

Landslide Classification – Referenced from Varnes, 1978.

Landslide Type	Landslide Description	Illustration
Rotational sliding	The landslide failure surface is curved concavely upward and the movement of mass is mainly rotational. Rotational movement causes back tilting of the displaced material near the headscarp.	
Translational sliding	The landslide mass moves along a planar failure surface with minor rotational movement.	
Earth flow	The movement of saturated fine-grained materials or clay bearing rocks. The displaced material forms a characteristic hourglass shape with an elongated flow path.	
Debris flow	The rapid movement of saturated, loose material caused by heavy precipitation and surface water flow. Commonly occurring on steep slopes.	
Debris avalanche	A type of debris flow that is *extremely* rapid.	
Rock fall	The separation of rocks and boulders along fractures, joints and bedding planes on steep slopes or cliffs. The movement is heavily influenced by mechanical weathering of the rock mass and gravity.	

Landslide characteristics – Modified after Varnes, 1978.



Likelihood – Used as a qualitative description of probability or frequency of the event/landslide.

Overland Flow Path – The predicated flow path of stormwater over the topography.

Permeability – The capacity of a material to allow water to pass through it. Clay materials are impermeable whereas gravels and sands are porous and therefore permeable.

Probability – A measure of the degree of certainty. This measure has a value between zero (impossibility) and 1.0 (certainty). It is an estimate of the likelihood of the magnitude of the uncertain quantity or the likelihood of the occurrence of the uncertain future event. There are two main interpretations:

(i) Statistical – frequency or fraction – The outcome of a repetitive experiment of some kind like flipping coins. It also includes the idea of population variability. Such a number is called an “objective” or relative frequentist probability because it exists in the real world and is in principle measurable by doing the experiment.
(ii) Subjective probability (degree of belief) – Quantified measure of belief, judgement, or confidence in the likelihood of a outcome, obtained by considering all available information honestly, fairly and with a minimum of bias. Subjective probability is affected by the state of understanding of a process, judgement regarding an evaluation or the quality and quantity of information. It may change over time as the state of knowledge changes.

Probability of Occurrence – used interchangeably with Likelihood.

Quantitative Risk Analysis – an analysis based on numerical values of the probability, vulnerability and consequences, and resulting in a numerical value of the risk.

Recurrence Interval (repeat period) – An estimated value of how often an event occurs based on the average time between passed events.

Regression – The continual movement of a landslide downslope and or widening/retreat of the headscarp.

The **Regulator** will be the responsible body/authority for setting Acceptable/Tolerable Risk Criteria to be adopted for the community/region/activity, which will be the basis for setting levels for Acceptable and Tolerable Risk in the application of the risk assessment guidelines.

Risk – A measure of the probability and severity of an adverse effect to health, property or the environment. Risk is often estimated by the product of probability x consequences. However, a more general interpretation of risk involves a comparison of the probability and consequences in a non-product form.

Risk Analysis – The use of available information to estimate the risk to individuals, population, property or the environment from hazards. Risk analyses generally contain the following steps: scope definition, hazard identification and risk estimation.

Risk Assessment – The process of risk analysis and risk evaluation.

Risk Control or Risk Treatment – The process of decision making for managing risk and the implementation or enforcement of risk mitigation measures and the re-evaluation of its effectiveness from time to time, using the results of risk assessment as one input.

Risk Estimation – The process used to produce a measure of the level of health, property or environmental risks being analysed. Risk estimation contains the following steps: frequency analysis, consequence analysis and their integration.

Risk Evaluation – The stage at which values and judgements enter the decision process, explicitly or implicitly, by including consideration of the importance of the estimated risks and the associated social, environmental, and economic consequences, in order to identify a range of alternatives for managing the risks.

Risk Management – The complete process of risk assessment and risk control (*or risk treatment*).

Runout Distance – The horizontal distance from the source area to the distal toe.

Susceptibility – see Landslide Susceptibility

Temporal-Spatial Probability – The probability that the element at risk is in the affected area at the time of the landslide.

Tolerable Risk – A risk within a range that society can live with so as to secure certain net benefits. It is a range of risk regarded as non-negligible and needing to be kept under review and reduced further if possible.

Transgression-regression cycles – Sedimentary deposits formed from cycles of sea level rise and fall.

Travel Angle – The angle from the crest of the source area to the distal toe of the debris (run out zone)

Vulnerability – The degree of loss to a given element or set of elements within the area affected by the landslide hazard. It is expressed on a scale of 0 (no loss) to 1 (total loss). For property, the loss will be the value of the damage relative to the value of the property; for persons, it will be the probability that a particular life (the element at risk) will be lost, given the person(s) is affected by the landslide.

ghd.com

→ The Power of Commitment

ISBN 978-1-991146-40-3 (PDF)
May 2024