Earthquake-Induced Landslide Forecast and Hazard Assessment, Bluff Hill, Napier

GJ Pradel
S Dellow
B Lukovic

GNS Science Consultancy Report 2019/179
April 2020

DISCLAIMER

This report has been prepared by the Institute of Geological and Nuclear Sciences Limited (GNS Science) exclusively for and under contract to Hawke’s Bay Regional Council. Unless otherwise agreed in writing by GNS Science, GNS Science accepts no responsibility for any use of or reliance on any contents of this report by any person other than Hawke’s Bay Regional Council and shall not be liable to any person other than Hawke’s Bay Regional Council, on any ground, for any loss, damage or expense arising from such use or reliance.

Use of Data:

Date that GNS Science can use associated data: December 2019

BIBLIOGRAPHIC REFERENCE

Pradel GJ, Lukovic B, Dellow GD. 2019. Earthquake-induced landslide forecast and hazard assessment, Bluff Hill, Napier. Lower Hutt (NZ): GNS Science. 17 p. Consultancy Report 2019/179.

CONTENTS

FIGURES

TABLES

EXECUTIVE SUMMARY

The 1931 Hawke’s Bay earthquake demonstrated that steep cliffs around the Bluff Hill area are susceptible to rockfalls and cliff collapses. Bluff Hill in Napier is a natural refuge from tsunami, and recent evacuation paths onto the hill have been identified and promoted for the Napier CBD and port area. With an earthquake-induced landslide (EIL) model now available, the ability exists to access the vulnerability of these evacuation paths and their susceptibility to future earthquake-induced rockfalls and cliff collapses.

The goal of this project was to model EILs based on 25-, 100-, 500-, 1000- and 2500-year return period peak ground accelerations (PGA) and identify existing infrastructure vulnerabilities to rockfalls and cliff collapses at Bluff Hill.

Key findings show that even though the probability of rockfall and/or cliff collapse is relatively low, they may still pose a risk to people, buildings and infrastructure, particularly access routes during a tsunami evacuation event, and their impacts should not be ignored. Roads around the Port of Napier and eastern Ahuriri suburb appear to be particularly vulnerable to being cut off by rockfall, and access from these areas to safe tsunami evacuation zones is likely to be disrupted in a larger earthquake event. It is likely necessary that more specific investigations are required here to develop a suitable evacuation plan for these areas.

It is suggested that roads directly adjacent to or within several pixel lengths from the modelled landslide hazards are carefully considered within any evacuation plans, where possible, and may require protection measures to be put in place due to the inherent risks and delays these hazards may cause. Roads that lie some distance downslope from the modelled landslides/rockfalls are similarly at risk of being subject to potential disruption. However, we cannot conclusively determine whether the runout material in these locations is sufficient enough to affect the routes in these locations, and further modelling to predict this will be required.

This page left intentionally blank.

1.0 INTRODUCTION

Bluff Hill in Napier is a natural refuge from tsunami arriving at the Hawke’s Bay coastline. After the 1931 Hawke’s Bay Earthquake, rockfall and cliff collapse were reported and photographed on the steeper slopes of Bluff Hill (Figure 1.1). In recent years, tsunami evacuation paths onto and up Bluff Hill have been identified and promoted for the Napier CBD and port area. With an earthquake-induced landslide (EIL) hazard model now available, it is possible to determine whether the planned tsunami evacuation paths are vulnerable to future earthquake-induced landslide, rockfall and cliff collapse.

This report is submitted by the Institute of Geological & Nuclear Sciences Limited (GNS Science) in response to a request from Lisa Pearse, Team Leader Hazard Reduction, Hawke’s Bay Civil Defence Emergency Management Group (HBCDEM), for Hawke’s Bay Regional Council. This report has been prepared with consideration of details supplied by Lisa Pearse and following the meeting between GNS and HBCDEM on 6th March 2019. It presents the results of the Bluff Hill EIL forecasting undertaken by GNS Science and impacts on potential tsunami evacuation routes along Bluff Hill.

1.1 Background to Project

The seismic hazard in the Hawke’s Bay Region is high because of its proximity to a convergent part of the Australia-Pacific tectonic plate boundary. One of the consequences of a high seismic hazard is EIL. Historically (since 1840), several earthquakes in the region have caused landslides and rockfalls (Figure 1.1).

Figure 1.1 Rockfall at Ahuriri caused by the Hawke’s Bay Earthquake in 1931 (GNS Science).

There are many different types of landslide failure mechanisms and, based on Cruden and Varnes (1996) and Hungr et al. (2014), typical failure modes for Bluff Hill are assumed to include:

- **Rock fall:** Detachment, falling, rolling and bouncing of rock fragments (Figure 1.1) (Hungr et al. 2014).
- **Boulder/debris/silt fall:** Detachment, fall, rolling and bouncing of soil fragments such as large clasts in soil deposits or blocks of cohesive (cemented or unsaturated) soil (Figure 1.1) (Hungr et al. 2014).
- **Gravel/sand/debris slide:** Sliding of a mass of granular material on a shallow, planar surface parallel with the ground (Figure 1.2) (Hungr et al. 2014).
- **Debris flowslide:** Very rapid to extremely rapid flow of sorted or unsorted saturated granular material on moderate slopes (Figure 1.3) (Hungr et al. 2014).
- **Soil slope deformation:** Deep-seated, slow to extremely slow deformation of a valley or hill slopes formed of soils (usually cohesive) (Figure 1.4) (Hungr et al. 2014).

Figure 1.2 Debris (gravel) slide caused by the Kekerengu Fault rupture in Clarence River following the 2016 Kaikōura Earthquake (GNS Science).

Figure 1.3 Debris flowslide resulting from the rupture of the Papatea Fault near Clarence River following the 2016 Kaikōura Earthquake (GNS Science).

Figure 1.4 Soil slope deformation associated with the Kekerengu Fault near the junction to Clarence River following the 2016 Kaikōura Earthquake.

The acquisition of high-quality landslide and related datasets has allowed GNS Science to develop a probabilistic EIL hazard model. With this model now available, it is possible to identify areas where a higher EIL hazard exists. When the EIL hazard is combined with infrastructure information, areas where the risks from EIL hazards are higher can be identified. Identifying these areas of elevated risk will improve community preparedness through better land-use planning decisions and emergency response plans.

1.2 Project Objectives (Scope)

The objectives of this project are to:

- Run the EIL hazard model for Bluff Hill at appropriate 100-, 500-, 1000- and 2500-year peak ground acceleration (PGA) shaking levels to determine the probabilities for EIL occurring at different localities.
- Overlay the existing infrastructure over the results of the EIL model runs.
- Report the results identifying existing infrastructure vulnerabilities to EIL at Bluff Hill.
- Present the results to the HBCDEM Group.

1.3 Site Description

Bluff Hill is located in the northeast of Napier City and reaches a maximum height of approximately 105 m above sea level (masl). For this report, ‘Bluff Hill’ refers to the summit and suburb, as well as Hospital Hill and elevated parts of Ahuriri suburb. The hill was historically known as Scinde Island when partly separated by swamps and estuaries from the mainland prior to the 1931 Napier Earthquake. The hill is predominately occupied by residential housing and roads, overlooking lower Ahuriri and estuary to the west and Napier central business district and city to the south. The area consists of moderately to steeply inclined cliff faces that tend to be covered by an assortment of vegetation, with the steepest cliffs located on the northeast of Bluff Hill overlooking the Port of Napier.

The geology of Bluff Hill consists primarily of the early Pleistocene (early Nukumaruan) Scinde Island Formation sedimentary rock (Kingma 1971; Boyle 1987; Beu 1995; Bland 2006; Lee et al. 2011). The formation is separated into five members:

- **Member A:** Basal layer of the Scinde Island Formation and the most widespread of the five members. It consists of strongly cross-bedded, differentially cemented, calcareous sandstone interbedded with lenses of sandy coquina limestone (Kingma 1971; Boyle 1987; Bland 2006).
- **Member B:** Located to the northern and western parts of Bluff Hill and consists of massive calcareous sandstone.
- **Member C:** Predominately outcrops to the south-western end and gradually thins to the north. It consists of thin alternating beds of shell hash, mudstone and cross-bedded limestone (Hutton 1886; Kingma 1971; Boyle 1987; Bland 2006).
- **Member D:** Thickest to the southeast of Bluff Hill and thins towards the south. It consists of sandstone and mudstone overlain by pumiceous muddy sandstone (Boyle 1987; Bland 2006).
- **Member E:** Stratigraphically the highest member, it is located to the southwest. It consists of barnacle-rich limestone and is unconformably overlain by Pleistocene loess (Boyle 1987; Bland 2006).

The Scinde Island Formation deposits, particularly the lower layers, are closely jointed and fractured and are locally overlain by Pleistocene river, lake and intertidal silts and clays of the Kidnappers Group and loess deposits up to a metre thick (Kingma 1971).

2.0 DATASETS

An EIL forecasting tool has been developed (described below in the methodology section). The tool requires several datasets to derive an EIL forecast map. The datasets the tool uses are described here.

2.1 Static Datasets

2.1.1 Digital Elevation Model (DEM)

The high-resolution digital elevation model used is the New Zealand 2012 8 m DEM from Land Information New Zealand (LINZ), available through the LINZ Data Service website.

2.1.1.1 Local Slope Relief (LSR)

A local slope relief model (LSR) has been calculated from the 8 m resolution DEM using focal statistics in ArcGIS. It represents the local height (and slope angle) of the sample grid cell relative to adjacent areas. It is calculated as the difference in elevation between the lowest elevation in an 8 m by 8 m grid cell, within an 80 m (ten 8 m cells) radius from the centroid of the given sample grid cell, and the mean elevation of that grid cell. Larger values of LSR represent sustained steep slopes that are affected by stronger ground shaking.

2.1.1.2 Slope Angle

A slope angle model has been calculated from the local hillslope gradient from the 8 m resolution DEM, adopting the mean value of all adjacent 8 m by 8 m cells. This variable is a proxy for the static shear stresses in the slope.

2.1.1.3 Local Hillslope Elevation

Local hillslope elevation has been calculated from the 8 m resolution DEM, adopting the mean value of adjacent 8 m by 8 m cells. This variable accounts for variable surface topography that can limit the size of the landslides.

2.1.2 Fault Distance

Distance to potentially seismogenic structures has been calculated from mapped active faults, as extracted from GNS Science’s Active Faults Database (accessed on 05/03/2018).

2.1.3 Geology

Geological units have been extracted from the NZL_GNS_250K_geological units layer of the NZL GNS 1:250K Geology dataset (2nd edition) (Heron 2018). Units have been grouped into four classes: Quaternary debris, Neogene sedimentary deposits, Cretaceous-Paleogene sedimentary deposits and Mesozoic basement greywacke.

2.2 Dynamic Datasets

2.2.1 Peak Ground Acceleration

Mean PGA have been derived from the 2010 GNS National Seismic Hazard Model (NSHM) for the Heretaunga Plains. PGAs were calculated for return periods of 25, 100, 500, 1000 and 2500 years.

Table 2.1 Maximum PGA values for different return periods calculated for the Napier area from the National Seismic Hazard Model (Rosser and Dellow 2017).

Hawke’s Bay Sites Unweighted Site Class D					
Annual Exceedance Probability (AEP)	0.04	0.01	0.002	0.001	0.0004
Return Period (Years)	25	100	500	1000	2500
PGA Value (g) at Napier/Hastings	0.14	0.25	0.42	0.51	0.64

3.0 METHODOLOGY

3.1 Background

The EIL forecasting tool has been developed to quantify the threat of landslide hazards resulting from earthquake ground shaking (Massey et al. 2018). The tool has been built within ESRI ArcGIS software using Python scripts. The processing within the EIL forecast tool is undertaken using ESRI ArcGIS tools (version 3.1) and Python scripting language (version 2.7.8).

The EIL tool requires five of the datasets (local slope relief, local hillslope elevation, slope angle, distance from active faults and geology, described above) as inputs to a static model of the landscape to which the dynamic PGA are applied to produce an EIL forecast map. The background and derivation of the EIL tool is based on work described in Massey et al. (2018). The tool has been designed to be used for response immediately (within a few minutes) after a major earthquake (PGAs of 0.2 g or greater). For this report we are using PGA annual exceedance probability (AEP) values rather than PGAs from specific earthquake events. The PGAs are provided from the NSHM rather than utilising measured PGA data coming off the monitoring network in real time.

The EIL tool is used in this report to produce maps showing landslide probabilities for specific earthquake shaking return periods. For this report, a uniform shaking level across the area of interest (Bluff Hill) over the range of selected return periods has been calculated from the NSHM (Table 2.1).

The EIL modelling does not consider variations in predicted PGAs caused by surface material moisture variations. A nominal storage of 50% is assumed as per the NIWA 2019 Soil Moisture Deficit (SMD) maps available on their website (https://niwa.co.nz/climate/nz-drought-monitor/droughtindicatormaps/soil-moisture-deficit-smd).

3.2 Pre-Processing

Pre-processing is undertaken to create the required static data layers from the source datasets. Static data layers have been generated nationally using Python scripts to create raster datasets (maps containing a grid of cells or pixels) at 32 m resolution. These are a too coarse resolution for adequately modelling Bluff Hill. For this report, the landslide probability has been calculated and presented for an 8 m resolution.

The LINZ 8 m DEM model has been used to generate the derived topographic datasets at 8 m resolution. The ArcGIS software MEAN function was used for generalising the Local Slope Relief and Slope Angle raster datasets, and the MAX function for generalising the Local Hillslope Elevation.

The fault distance raster dataset, created nationally at 32 m resolution using the Euclidean Distance tool with the Active Fault layer (AF250_05032018), has been clipped and resampled to 8 m for the Bluff Hill modelling.

The geological units raster dataset created nationally at 32 m resolution is based on four unit classes:

1. Quat_Debris
2. Neo_Sedimentary

3. Cret_Paleo_Sedimentary
4. Base_Greywacke.

These classes are quantified in the GeologyCode field as integer values (equal to the order number in the above list). These classes are broadly aligned to each unit's soil and rock strength, either with known statistically similar earthquake shaking performance or based on the expert knowledge of experienced engineering geologists. There are uncertainties in extrapolating the EIL forecast beyond the boundaries of the Kaikōura earthquake inventory, but it is not yet possible to quantify these uncertainties (Massey et al. 2018).

The five static datasets have been combined into a single model of 8 m x 8 m grid cells for Bluff Hill from the five source datasets. Each cell in the model is attributed with elevation, slope angle, local slope relief, distance from active faults and geology.

3.3 Processing

Landslide probabilities have been derived based on the performance of slopes at different levels of shaking during historical earthquakes. This analysis is currently based on the high-quality EIL dataset compiled after the 2016 Kaikōura Earthquake and the modelled variation of ground shaking during this earthquake. The processing for Bluff Hill follows the national-scale modelling by calculating landslide probabilities for each grid cell (Massey et al. 2018). The processing is done by running a sequence of Python scripts, collectively known as runEILForecast.py, that complete different elements of the required processing. The variables are passed from script to script, and the individual scripts cannot be run separately.

The control script imports the required Python modules and sets scripting variables. It checks if required static data, input files and map templates are present and terminates processing if any of the required data is missing. It creates a processing folder, processing and scratch geodatabases and an output folder, if they do not exist. After the processing is finalised, a result folder is created within the script and the final outputs, required for producing maps, are copied there. The output table and maps are also placed in the result folder.

3.4 Output

The results of running the EIL tool show the calculated probability of the 8 m x 8 m grid cell being the source area for a landslide/rockfall given the PGA applied at the site. The EIL tool does not show the area potentially affected by runout of debris from landslides. Determining the extent of landslide runout and associated probabilities requires additional analysis that the EIL tool is not yet capable of performing or the application of other tools.

The range of probabilities calculated for grid cells upslope from a tsunami evacuation route show the variation in likelihood for the occurrence of a landslide/rockfall. A landslide/rockfall occurring from locations with a high probability could block access along these routes or kill/injure people using the routes after a local, long, strong earthquake (or its aftershocks) when the message is to evacuate to higher ground immediately.

4.0 LANDSLIDE TOOL MAPS

Class maps that show the probability of rockfalls occurring across the given area were created from the EIL forecasting tool for each of the given return periods (25, 100, 500, 100 and 2500 years).

The class maps range from 0% (low to no probability landslides occurring) to 100% (high probability landslide occurring). It should be noted that the modelling of the landslides here represents the source of the landslide failure and not the runout associated with such an event. To assess the runout potential of these materials further modelling is required, which is outside the scope of this report.

4.1 25 PGA

Figure 4.1 shows the class map spatial distribution of landslide probability with a PGA acceleration of 0.14 g for a 25-year return period (Rosser and Dellow 2017). A low landslide probability (1–10%) is predicted to the northeast of Bluff Hill with a few, very minor, low probability landslides also interpreted across Bluff Hill. However, the modelled source material of the landslide to the northeast sits within proximity of Breakwater Road, which is located downslope.

4.2 100 PGA

Figure 4.2 shows the class map spatial distribution of landslide probability with a PGA acceleration of 0.25 g for a 100-year return period (Rosser and Dellow 2017). A low landslide probability (1–10%) is predicted to the northeast of Bluff Hill, with a few minor low probability landslides scattered across Bluff Hill. The main predicted landslide source sits upslope and within close proximity from Breakwater Road, which runs along the north-eastern front of Bluff Hill.

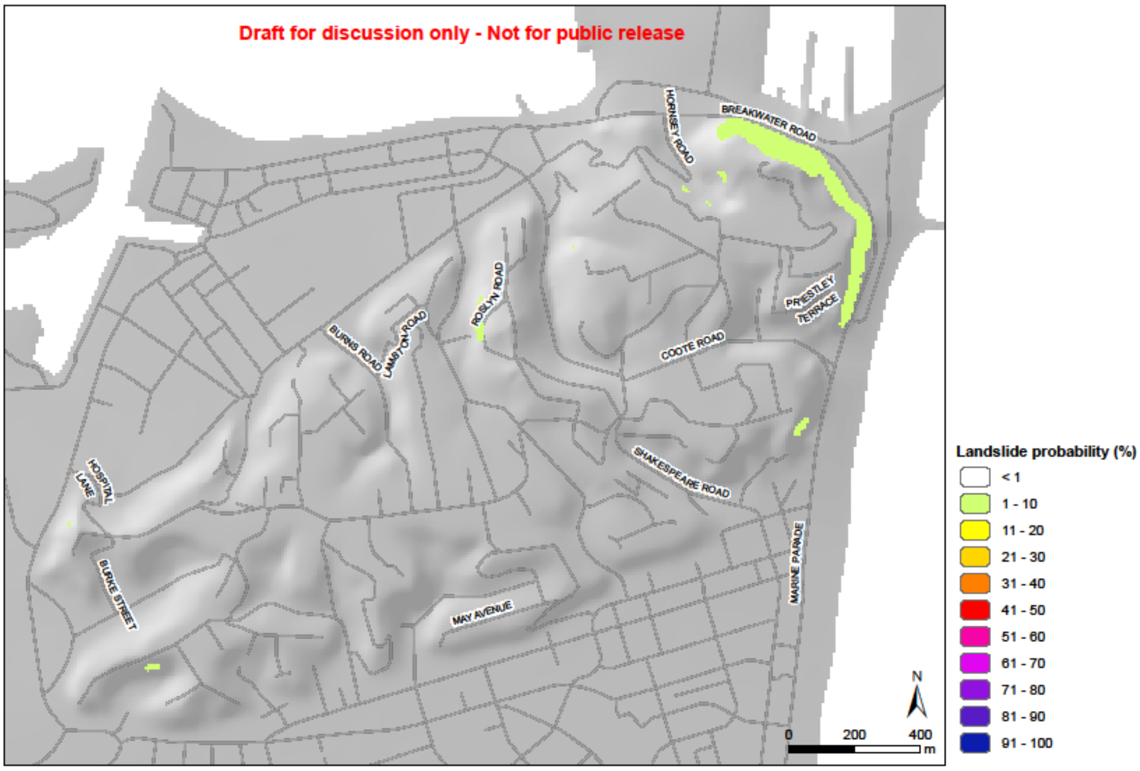

Figure 4.1 EIL probability class colour map of Bluff Hill, Hawke's Bay based on a 0.14 g PGA at a return period of 25 years.

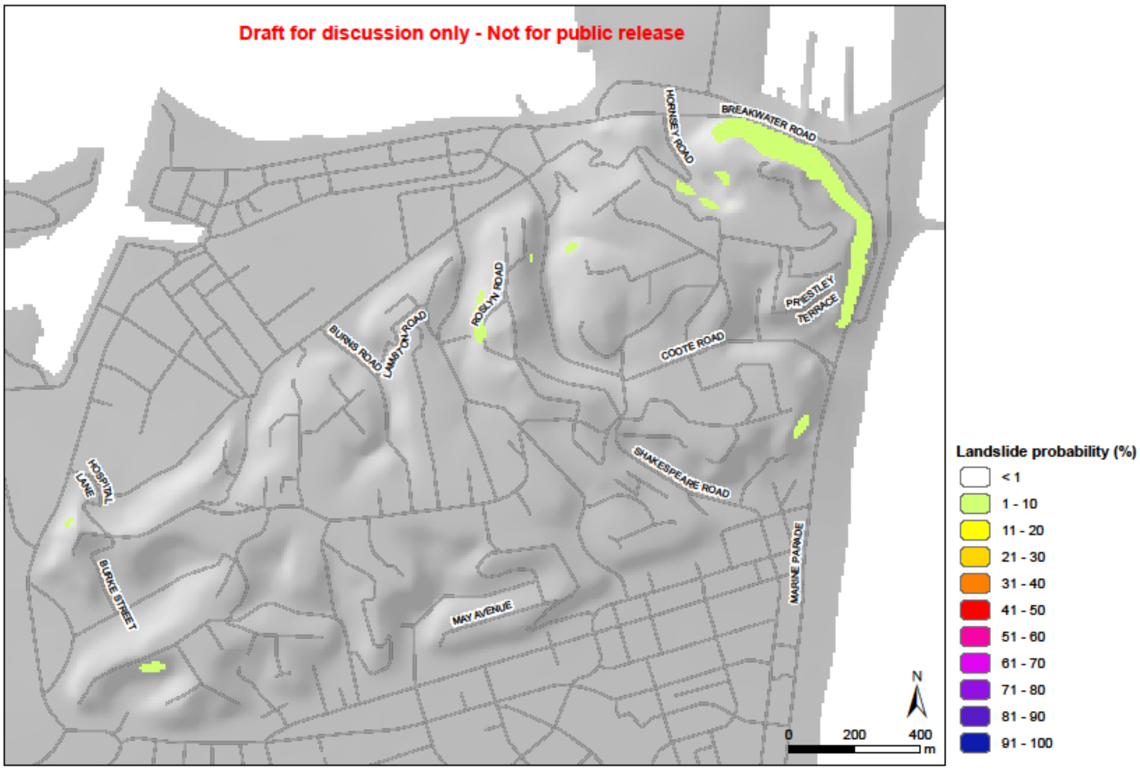

Figure 4.2 EIL probability class colour map of Bluff Hill, Hawke's Bay based on a 0.25 g PGA at a return period of 100 years.

4.1 500 PGA

Figure 4.3 shows the class map spatial distribution of landslide probability with a PGA acceleration of 0.42 g for a 500-year return period (Rosser and Dellow 2017). A low landslide probability (1–10%) is similarly observed, concentrated to the northeast of Bluff Hill. Several smaller volume low-probability landslides are also noted scattered across Bluff Hill, with several observed within proximity to the local roads, including Breakwater Road, Hornsey Road, Shakespeare Road, Roslyn Road and Lambton Road.

4.2 1000 PGA

Figure 4.4 shows the class map spatial distribution of landslide probability with a PGA acceleration of 0.51 g for a 1000-year return period (Rosser and Dellow 2017). A low landslide probability (1–15%) is similarly predicted in northeast parts of Bluff Hill. Several smaller volume landslides are also noted scattered across the north and southwest of Bluff Hill. These similarly are within close proximity to a number of roads as mentioned for the 500 PGA, including Marine Parade and May Ave.

4.3 2500 PGA

Figure 4.5 shows the class map spatial distribution of landslide probability with a PGA acceleration of 0.64 g for a 2500-year return period (Rosser and Dellow 2017). A noticeable increase in the landslide number and size is predicted, though all landslides remain as a low landslide probability (1–20%). These predicted landslides are predominately concentrated to the northeast and southwest of Bluff Hill, with several predicted to lie in close proximity to several local roads (as detailed above) that also include Priestly Terrace, Coote Road, Burns Road, Burke Street and Hospital Lane. These landslides are predicted to have a larger impact on these roads due to the increased size of the predicted landslides.

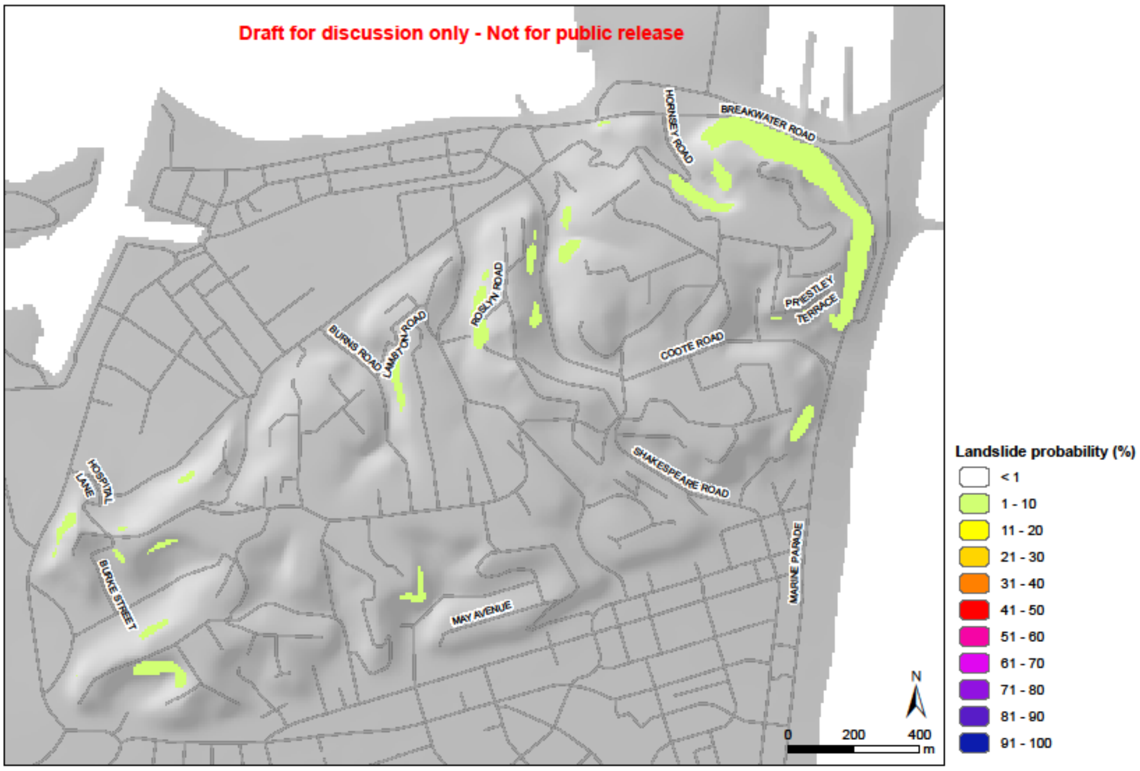

Figure 4.3 EIL probability class colour map of Bluff Hill, Hawke's Bay based on a 0.42 g PGA at a return period of 500 years.

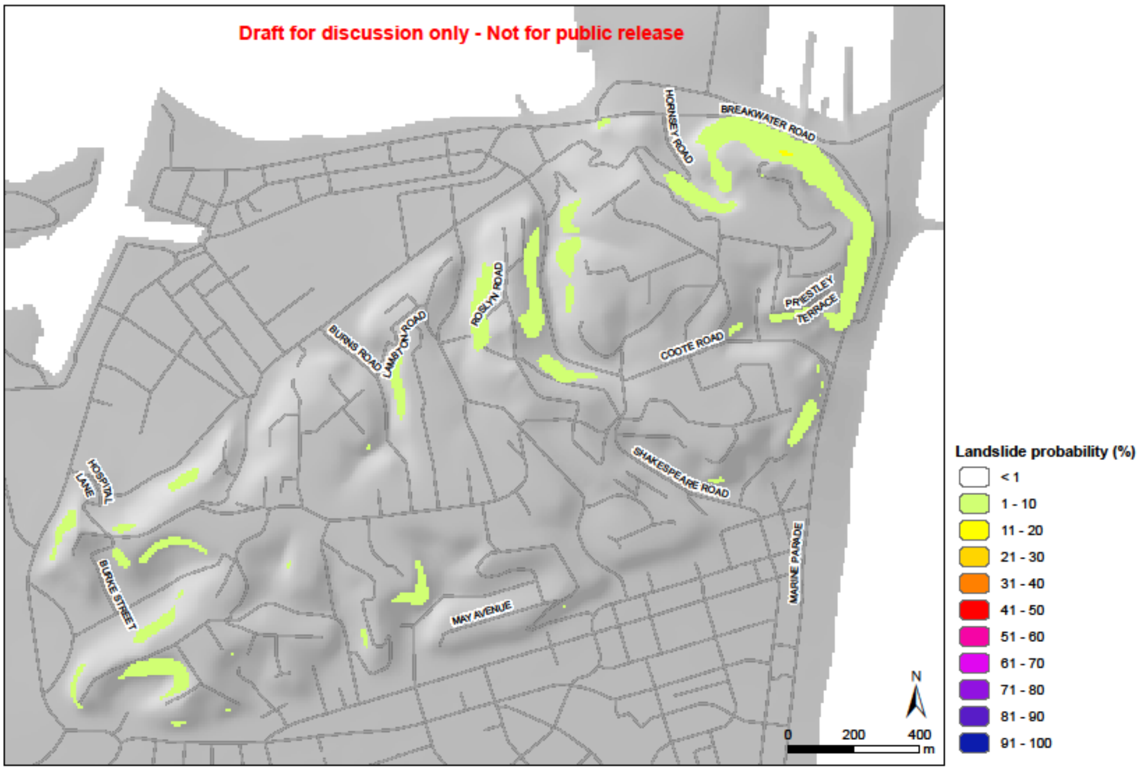

Figure 4.4 EIL probability class colour map of Bluff Hill, Hawke's Bay based on a 0.51 g PGA at a return period of 1000 years.

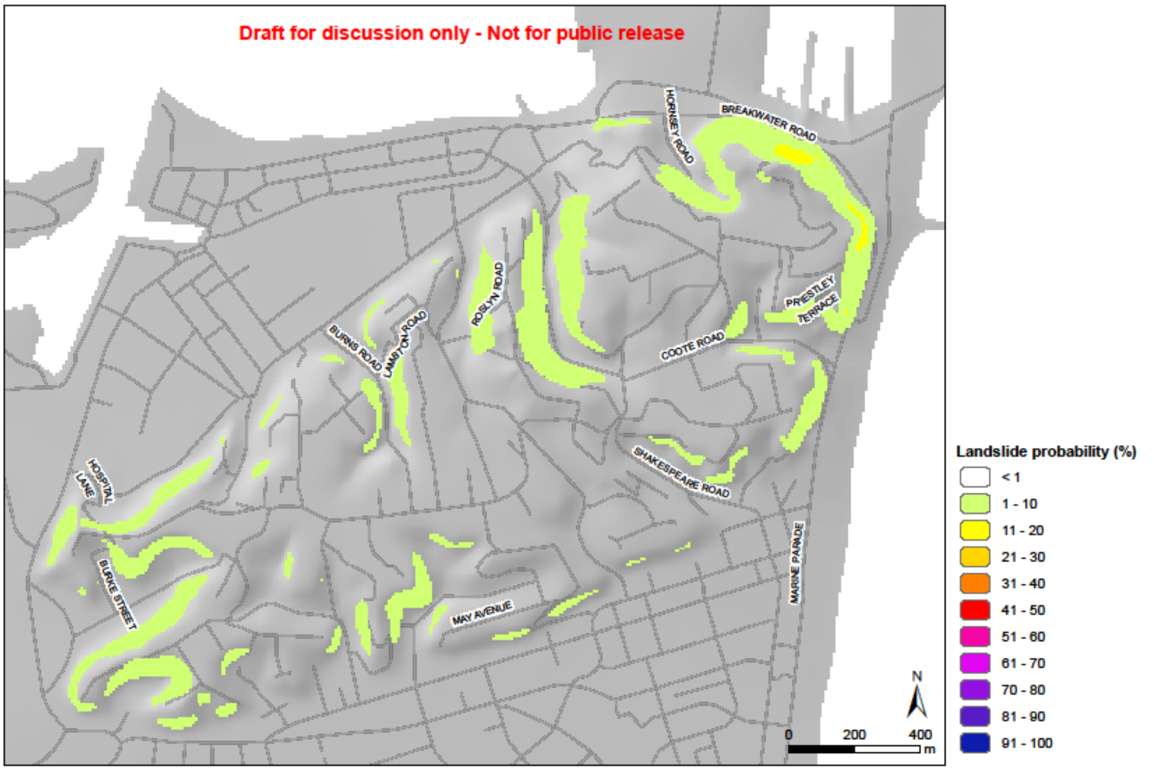

Figure 4.5 EIL probability class colour map of Bluff Hill, Hawke's Bay based on a 0.64 g PGA at a return period of 2500 years.

5.0 DISCUSSION

The EIL modelling on Bluff Hill shows that potentially unstable areas occur across Bluff Hill, particularly on the steep northeast flank, including several in proximity to roads across and surrounding Bluff Hill. The modelling results show the probability of these landslides is low (<20%). However, they may pose a risk to people, buildings and infrastructure, and some may be a hazard to potential tsunami evacuation routes.

The results of our modelling show the probability of areas across Bluff Hill acting as the source for predicted landslide events. The runout of the debris generated by these failures has not been modelled. This assessment, using the EIL forecast tool, has identified areas across Bluff Hill vulnerable to landslide events. This will allow the identification of sites where site-specific runout modelling may be needed to better understand the risks to users of tsunami evacuation routes.

Based on a 25- and 100-year return period PGA (0.14 g and 0.25 g, respectively; Rosser and Dellow 2017), Bluff Hill is expected to experience very minor disruption from landslides/rockfall. Our modelling suggests this is likely to be concentrated along the northeast of Bluff Hill (Bluff Hill Lookout). Breakwater Road, which runs downslope of the north-eastern edge of Bluff Hill, is proximal to modelled landslide/rockfall sources and is a potential hazard to road users. This may affect access to and from the Port of Napier and is a vulnerable route at these low levels of shaking. It is recommended that areas where landslides and rockfall are a potential hazard are carefully considered within any evacuation plans, where possible, and may require specific engineering solutions to improve slope stability.

The EIL maps based on a PGA with a 500-, 1000- and 2500-year return period (0.42 g, 0.51 g and 0.64 g, respectively; Rosser and Dellow 2017) show an increase in rockfall / cliff collapse distribution and source area size across Bluff Hill compared to those discussed above. They pose an increased risk to several roads across the area that may provide vital routes during a tsunami evacuation. Roads that are within several pixel lengths of the modelled landslides/rockfalls are at risk of debris causing disruption to these routes. These roads have been noted in Section 4 of this report. It is suggested that roads directly adjacent to or within several pixel lengths of the modelled landslides are carefully considered when distinguishing any evacuation routes due to the inherent risks and delays they may cause. Consequently, it may be necessary to look at engineering solutions to mitigate the effects of potential landslides along these roads. Roads that lie some distance downslope from the modelled landslides/rockfalls are similarly at risk of being subject to potential disruption. However, we cannot conclusively determine whether the runout material in these locations is enough to affect the routes in these locations, and further modelling to determine this is required.

Based on historic slips observed on and around Bluff Hill, runout material is expected to consist of anything between boulders greater than 2 m in size to fine gravels and silts. These materials are expected to be relatively easy to clear due to the generally weak nature of the rocks located on Bluff Hill. It is assumed that block sizes of greater than 2 m will need to be broken to remove them, but this should be achievable with an excavator jack hammer attachment. Aftershocks are likely to result in further material coming off slopes, with the amount of material coming off the slope dependent on the PGA of the aftershocks (Figure 5.1), as described by Massey et al. (2015). Field data and modelling from the 2011 Christchurch earthquake and subsequent aftershocks suggests that higher and steeper cliffs tend to amplify ground shaking to produce larger volumes of debris along with changes in cliff geology.

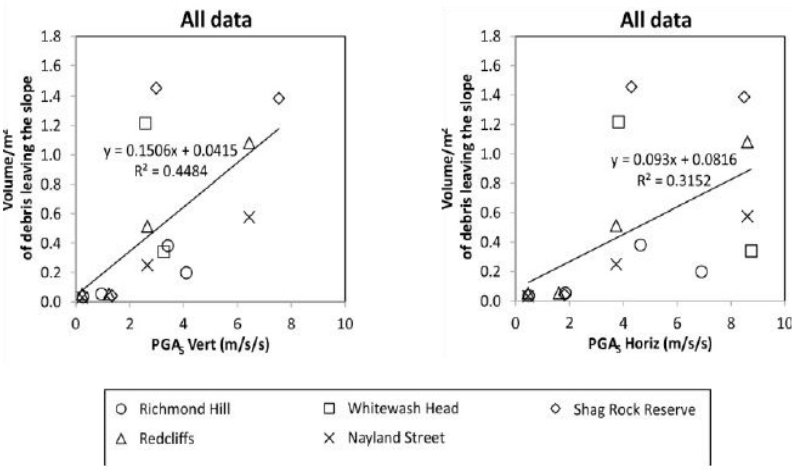

Figure 5.1 Relationship between the volume of debris leaving the cliffs and the synthetic earthquake parameters of PGA modelled after cliff failures during the 2011 Christchurch earthquake (Massey et al. 2015).

The Port of Napier and suburb of eastern Ahuriri are particularly vulnerable to being cut off by landslides/rockfalls (Figure 5.2), and access from these areas to evacuation zones that are safe from tsunami is likely to be disrupted in a larger earthquake event. Breakwater Road, Hornsey Road and Shakespeare Road are particularly vulnerable paths likely to be affected by landslide debris around these areas. This report has identified sites where more specific investigations, for example, rockfall runout modelling, are required to develop a suitable evacuation plan for these areas. Evacuation routes will need to be looked at carefully across these areas to provide suitable and safe areas for people to move through during a tsunami evacuation.

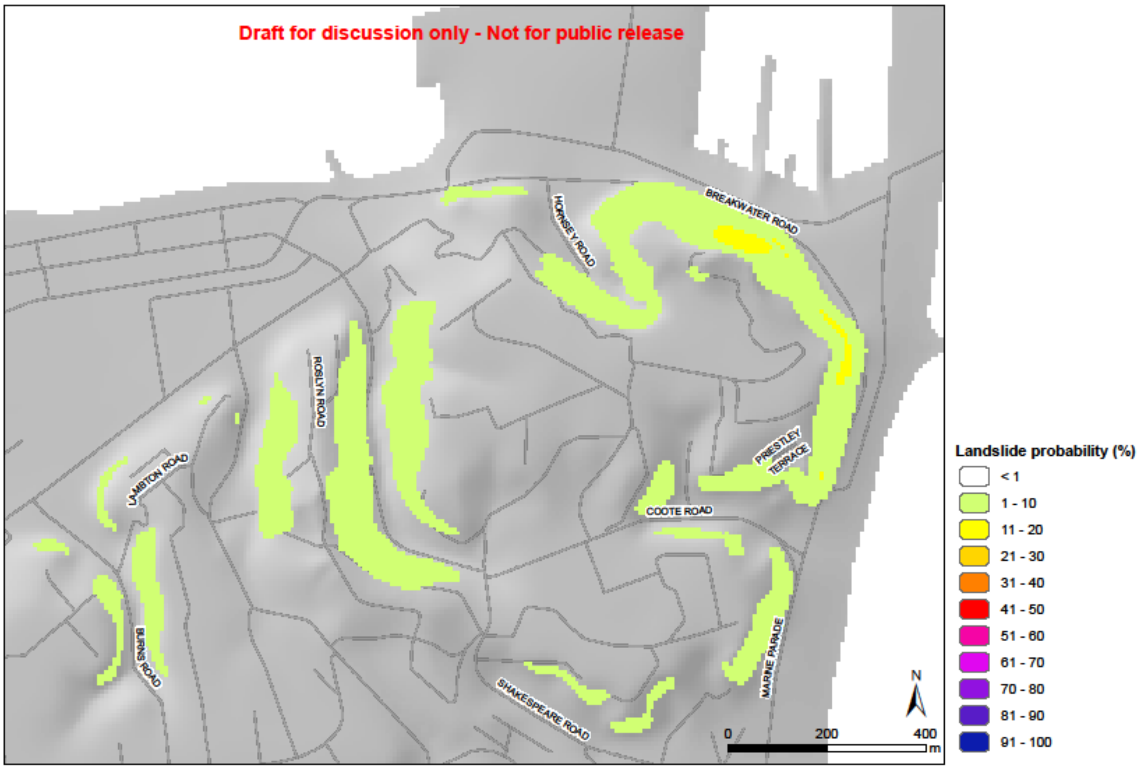

Figure 5.2 Class map showing that road networks near the Port of Napier and eastern Ahuriri are likely to be affected by EIL.

6.0 CONCLUSION

Bluff Hill is a natural refuge from tsunami arriving at the Hawke’s Bay coastline; however, rockfall and cliff collapses have been reported and photographed (Figure 1.1) from the steep slopes. In recent years, tsunami evacuation paths onto and up Bluff Hill have been identified and promoted for the Napier CBD and port area (Ahuriri). The EIL forecasting tool has identified several vulnerable areas prone to rockfalls and cliff collapses that may affect current tsunami evacuation plans.

Several key routes accessing Bluff Hill are identified in proximity to areas modelled as susceptible to rockfall/cliff collapse. Though no specific modelling of the runout material has been undertaken, in the event of a rockfall/cliff collapse they may cause disruption to tsunami evacuation routes. As such, it is recommended that routes, particularly those downslope and within proximity to the modelled rockfalls, are carefully considered when distinguishing any evacuation routes, and it may be necessary to look at engineering solutions to mitigate the effects of potential landslides along these routes.

Routes accessing Bluff Hill from the Port of Napier and Ahuriri suburb are particularly vulnerable to rockfall and cliff collapse scenarios. Special attention will be required to assess suitable and safe routes for evacuations in the event of a tsunami. Furthermore, no assessment of the potential runout of the modelled landslide sources has been undertaken. As such, we are unable to assess the impact that all the potential rockfalls/cliff collapses may have, particularly those landslides that lie some distance from roads. Further site-specific modelling is required to determine the runout potential at locations where rock/cliff collapse could impact tsunami evacuation routes.

7.0 ACKNOWLEDGEMENTS

The authors would like to thank Dr Kyle Bland and Dr Martin Rattenbury for reviewing earlier drafts of this report.

8.0 REFERENCES

Beu AG. 1995. Pliocene limestones and their scallops: lithostratigraphy, pectinid biostratigraphy and paleogeography of eastern North Island Late Neogene limestone. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences. 243 p. (Institute of Geological & Nuclear Sciences monograph; 10).

Bland KJ. 2006. Analysis of the central Hawke's Bay sector of the Late Neogene forearc basin, Hikurangi Margin, New Zealand [PhD thesis]. Hamilton (NZ): University of Waikato. 2 v.

Boyle SF. 1987. Stratigraphy and sedimentation of Scinde Island Formation, Napier: mixed terrigenous-carbonate shelf facies in a late Pliocene forearc basin [MSc thesis]. Hamilton (NZ): University of Waikato.

Cruden DM, Varnes DJ. 1996. Landslide types and processes. In: Turner AK, Schuster RL, editors. *Landslides: investigation and mitigation*. Washington (DC): Transportation Research Board. p. 36–75. (Special Report; 247).

Heron DW, custodian. 2018. Geological map of New Zealand. 2nd ed. Lower Hutt (NZ): GNS Science. Scale 1:250,000. (GNS Science geological map; 1).

Hungr O, Leroueil S, Picarelli L. 2014. The Varnes classification of landslide types, an update. *Landslides*. 11(2):167–194. doi:10.1007/s10346-013-0436-y.

Hutton FW. 1886. On the geology of Scinde Island. *Transactions and proceedings of the New Zealand Institute*. 18(1885):327–332.

Kingma JT. 1971. Geology of the Te Aute subdivision. Lower Hutt (NZ): New Zealand Geological Survey. 173 p. (New Zealand Geological Survey bulletin; 70).

Lee JM, Bland KJ, Townsend DB, Kamp PJJ. 2011. Geology of the Hawke's Bay area [map]. Lower Hutt (NZ): GNS Science. 1 folded map + 93 p., scale 1:250,000. (Institute of Geological & Nuclear Sciences 1:250,000 geological map; 8).

Massey CI, Richards L, Della-Pasqua FN, McSaveney MJ, Holden C, Kaiser AE, Archibald GC, Wartman J, Yetton M. 2015. Performance of rock slopes during the 2010/11 Canterbury earthquakes (New Zealand). In: Hassani F, editor. *Proceedings: the 13th International Congress of Rock Mechanics: ISRM Congress 2015: innovations in applied and theoretical rock mechanics, May 10–13, 2015, Montreal, Canada*. [Montreal (QC)]: Canadian Institute of Mining Metallurgy and Petroleum.

Massey CI, Townsend DB, Rathje E, Allstadt KE, Lukovic B, Kaneko Y, Bradley B, Wartman J, Jibson RW, Petley DM, et al. 2018. Landslides triggered by the 14 November 2016 Mw 7.8 Kaikoura earthquake, New Zealand. *Bulletin of the Seismological Society of America*. 108(3B):1630–1648. doi:10.1785/0120170305.

Rosser BJ, Dellow GD, compilers. 2017. Assessment of liquefaction risk in the Hawke's Bay. Volume 1: the liquefaction hazard model. Lower Hutt (NZ): GNS Science. 114 p. Consultancy Report 2015/186. Prepared for Hawke’s Bay Regional Council.

www.gns.cri.nz

Principal Location

1 Fairway Drive, Avalon
Lower Hutt 5010
PO Box 30368
Lower Hutt 5040
New Zealand
T +64-4-570 1444
F +64-4-570 4600

Other Locations

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin 9054
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
Private Bag 2000
Taupo 3352
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road
PO Box 30368
Lower Hutt 5040
New Zealand
T +64-4-570 1444
F +64-4-570 4657