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THE USE OF EMPIRICAL METHODS TO PREDICT LANDSLIDE RUNOUT FOR USE IN RAPID LANDSLIDE RISK ASSSESSMENTS FOLLOWING CYCLONE GABRIELLE, NEW ZEALAND

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ABSTRACT

In February 2023, a severe weather event triggered widespread landslides across the coastal towns of Muriwai, Karekare and Piha, New Zealand, causing extensive damage and resulting in fatalities. In response, there was an urgent need to conduct area-wide landslide risk assessments on individual properties with respect to future debris flow hazards. This paper focuses on the development of rapid methods to predict landslide runout, using established empirical methods. With an inventory of 160 mapped landslides empirical-statistical relationships were established between runout distance, landslide volume, and downslope angle. Variation in data correlations ultimately necessitated the adoption of separate empirical models for Muriwai and Piha/Karekare.

These simple empirical-statistical models were combined with flow accumulation modelling to predict both landslide distance and direction. The method ultimately proved highly effective for the rapid delivery of risk assessments but highlighted the importance of using observational data, incorporating site-specific factors that influence landslide runout behaviour and applying a degree of judgement.

1 INTRODUCTION

Cyclone Gabrielle was an extreme weather event that occurred in February 2023, causing widespread flooding and >140,000 landslides (Geonet, 2023) across regions in the north and east of New Zealand's North Island. At $14.5 billion, the event became the costliest weather-related disaster in the country's history (phcc.org.nz). Dozens of landslides occurred in the coastal settlements of Muriwai, Piha and Karekare, located in the Waitakere Ranges region on the West Coast of Auckland, resulting in widespread damage to built infrastructure and the loss of two lives.

Prior to Cyclone Gabrielle the Auckland region was already under a state of emergency following a series of extreme weather events in January 2023 including the "Auckland Anniversary" storm when 160 mm of rainfall fell in just 6 hours, estimated to be a 1 in 250-year event (NIWA, 2023). Critically therefore it is implied that the slopes that failed in Muriwai, Piha and Karekare were already subject to a reduction in strength due to oversaturation.

As part of the emergency response following the event Auckland Council completed a preliminary assessment of risk to life using the rapid building assessment placarding system (building.govt.nz) in which buildings were either given unrestricted access (white placard), restricted access (yellow placards) or prohibited access (red placards). Following the initial emergency response an area-wide quantitative risk assessment was carried out on individual placarded properties to assess risk to life with respect to future landslide hazards, using the Australian Geomechanics Society Landslide Risk Management Guidelines, commonly referred to as AGS (2007).

A crucial element of the quantitative risk assessment process is understanding both the direction and reach of a future landslide hazard. Given the urgency for an outcome for homeowners and the requirement for speed and consistency in the assessments to facilitate the Auckland Council policy developed for a "buy out scheme" (Roberts, 2024), a rapid method for predicting landslide runout was required. This paper discusses the use of published empirical methods to develop predictive landslide runout models using observed landslide behaviour from the previous event which subsequently informed the quantitative risk assessments.

2 LANDSLIDE RISK ASSESSMENT PROCESS

Use of AGS (2007) quantitative risk assessment to estimate risks to loss of life for the person-most-at-risk was mandated by Auckland Council to be applied to each individual property. The Individual Risk-to-Life is defined as the risk of fatality or injury to any identifiable (nominated) individual who lives within the zone impacted by the landslide; or who follows a particular pattern of life that might subject them to the consequences of the landslide. In this instance this was a person occupying a building at risk of being impacted by a landslide. The risk of 'loss-of-life' to an individual is calculated from:

$$R_{(LoL)} = P_{(H)} x\, P_{(S:H)} x P_{(T:S)} x V_{(D:T)} \quad (1)$$

Where,

$R_{(LoL)}$ is the risk (annual probability of loss of life (death) of an individual).

$P_{(H)}$ is the annual probability of the landslide.

$P_{(S:H)}$ 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.

$P_{(T:S)}$ 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.

$V_{(D:T)}$ is the vulnerability of the individual (probability of loss of life of the individual given the impact).

The main objective of the risk evaluation is to compare the assessed risk to risk levels that are considered acceptable or tolerable to the community to enable informed policy decisions. These risk levels ultimately formed the basis of categorising each property for the "buy out" scheme and revising the original placards given during the rapid building assessment process. The risk acceptance criteria adopted by Auckland Council was a tolerable risk value of 10^{-4}/annum. It is important to distinguish between "acceptable risks" and "tolerable risks". AGS (2007) states that tolerable risks are 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 usually considered to be one order of magnitude lower than tolerable risks.

It is essential to recognise that there is an inherent level of uncertainty within the quantitative risk assessment process. Typically landslide risk assessments are based on a variety of different information that ranges from well-established knowledge to judgements, educated guesses and tentative assumptions. The effect of uncertainty is not usually implicitly stated. One of the main factors that influences the dependability of a landslide risk assessment is the nature and quality of evidence used to generate probability. In this study, the use of observed landslide behaviour from the previous event has been calibrated with published empirical methods for predicting landslide runout when estimating the probability of spatial impact ($P_{(S"H)}$).

3 STUDY AREA

The study areas are situated on the west coast of Auckland (Figure 1). Piha and Karekare are located within the Waitakere Ranges and Muriwai is approximately 8 km north of the ranges. The geomorphological and geological settling at Piha and Karekare are in contrast to those in Muriwai.

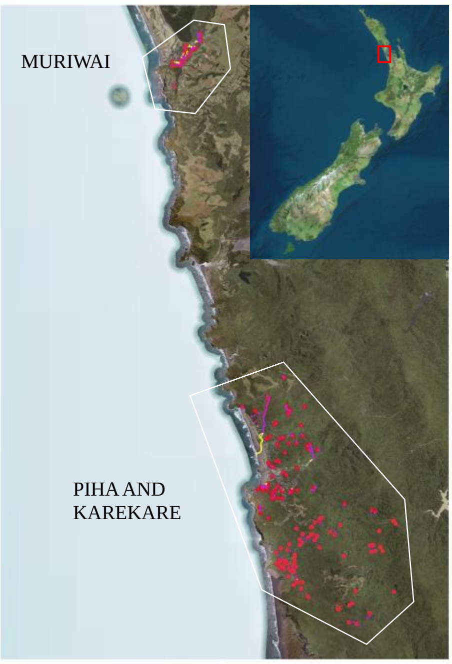


Figure 1: Landslides mapped in the coastal settlements of Muriwai, Piha and Karekare on the West Coast of Auckland

3.1 GEOMORPHOLOGICAL SETTING

Muriwai is characterised by an approximate 1.5 km-long escarpment that divides the township (Figure 2). The majority of the settlement is situated on the low-lying slopes beneath the escarpment and associated coastal terrace to the west (near sea level). There is a vertical elevation difference of approximately 80 m between the lower terrace and the higher plateau above the escarpment to the south and east. The centre of the escarpment is delineated by a north-west trending ridgeline, where slopes on the escarpment north of the ridgeline are typically 30° and have an 80 m vertical elevation and the slopes to the south are less well defined and variably have less than 50 m vertical elevation. The edge of the plateau is characterised by distinct crescent shaped scarps associated with past landslide events.

Piha and Karekare are situated on the western sloping margin of the Waitakere Ranges, which in contrast to the Muriwai area are characterised by a relatively steep, dissected topography with sharp ridgelines (Figure 2). The slopes are typically forested with dense native vegetation. Piha, approximately 3.5 km north of Karekare is bisected by the Piha Stream which divides the southern and central portions of the settlement. Although the majority of the settlement occupies much of the coastal backshore and elevated sand dunes, many properties also occupy the gently sloping, low lying stream flood plains in the central portion of the settlement as well as relatively steep hillsides in the southern portion up to 280 m RL. The settlement of Karekare occupies less of the low lying coastal area and is linearly distributed along two main roads (Karekare Road and Lone Kauri Road) which traverse both the low lying flood plain of Karekare Stream within the main valley feature and steep hillsides up to 320 m RL. Geomorphic features interpreted as relic landslide scarps are also common in the landscape.

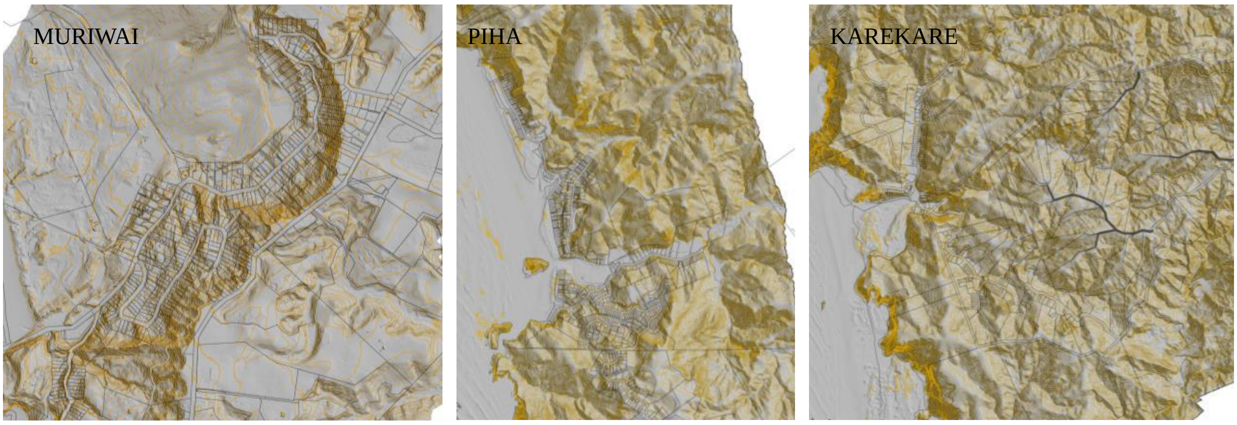


Figure 2: Muriwai and Piha/Karekare areas exhibit significantly different geomorphological characteristics

3.2 GEOLOGICAL SETTING

The geomorphological features described above are generally a consequence of the underlying geology. Muriwai is underlain by the Awhitu Sand Formation, part of the Kaihu Group coastal deposits (Pliocene age <2 Mya), which unconformably overly Miocene age volcanic and volcaniclastic deposits, and form the escarpment slopes. The Awhitu Sand Formation is characterised by dense to very dense sand in the top 30 m generally comprising fine to coarse clayey sand. Below 30 m the formation becomes a moderately weathered, massive to thickly bedded sandstone with very low to low strength. The beds are subhorizontal, discontinuous and cross bedded, consistent with costal dune formation, notably containing occasional discontinuous laminated to thick layers (generally <0.1 to 1 m) and lenses of silt, clay and peat.

The Awhtiu Sands have relatively high concentrations of iron which has oxidised near the modern day surface developing a binding cement giving the sands rock mass properties. The upper profile has been less affected by iron cementation and/or prone to dissolution due to exposure to weathering. The occurrences of fine grained or highly cemented layers tend to act barriers to groundwater, resulting in localised saturation of unconsolidated layers.

The hillsides in Karekare and Piha are underlain by the Piha Formation and Lone Kauri Formation, part of the Waitakere Group Volcanics. The Waitakere Ranges, which formed approximately 25 Mya are the remnants of a large volcanic system, the centre of which was approximately 200 km offshore. The Piha Formation and Lone Kauri Formation are submarine volcanic breccia conglomerate and terrestrial extrusive (subaerial basaltic andesite flows and pyroclastics) and shallow intrusive rocks, respectively. The rock mass is similarly massive with widely spaced joints. Critically the soil weathering profile developed within each formation is shallow (<1 m) typically comprising silts and clays with gravel to boulder sized rock fragments. Colluvial deposits are common on lower slopes and within incised gullies.

4 LANDSLIDE HAZARDS AND INVENTORY

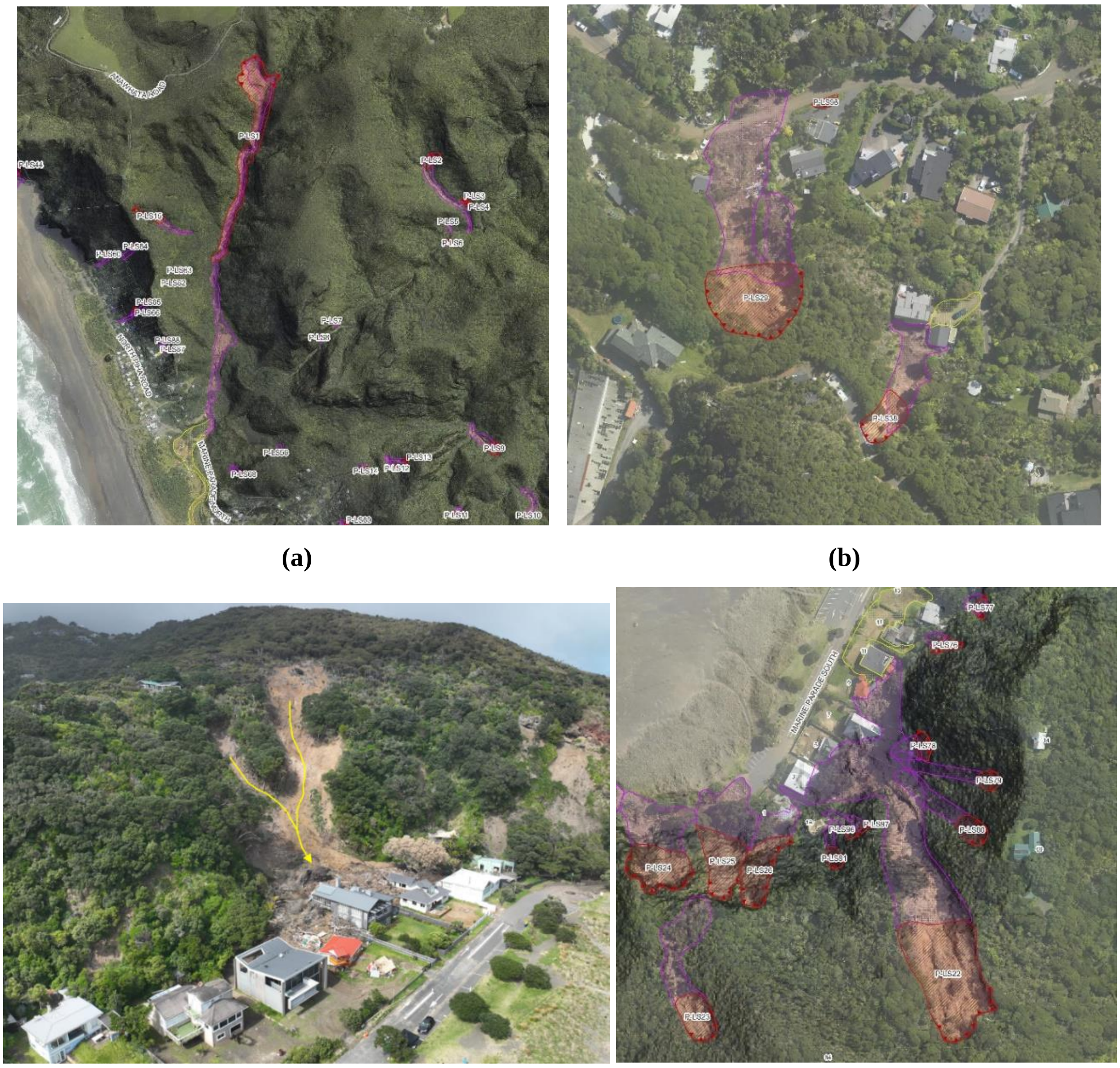
Following the event Auckland Council captured high resolution LiDAR data and aerial photography of the study areas. An attempt was made to undertake a DEM change analysis using pre event LiDAR data (LINZ, 2018) to identify landslides through obvious areas of ground surface change between the pre and post event DEM's, however this provided mixed results, potentially a result of contrasting resolution and survey techniques. Ultimately it was manual work with aerial photography in combination with the new LiDAR data which proved the most effective way to systematically map over 200 landslides, recording characteristics such as the zone of depletion and zone of accumulation. Subsequent targeted ground truthing was pivotal to confirm the presence of landslides and their runout extents as well as develop observational engineering geological models for each site under assessment.

Landslides that occurred on natural slopes throughout Muriwai, Piha and Karekare initiated as small to large slides (either translational or rotational) at their source area which subsequently became fluidised under surface and subsurface water flows to transition into debris flows, defined as extremely rapid debris flows according to the Hungr et al. (2014) classification system. A debris flow is referred to exclusively by Hungr et al. (2014) as a channelised landslide, whereas a landslide consisting of flowing debris on an open slope is referred to as a debris avalanche. In this study, the term debris flow is adopted universally. A common factor across the entire study areas was the relatively shallow depth of the initial slides, which was generally <1m occasionally up to 2m.

In Muriwai landslides initiated from a common source area, the crest of the main escarpment (Figure 3). The main scarps were measured up to 70 m in width, and they typically had a runout which extended well beyond the base of the escapement on the flatter coastal terrace below. Smaller landslides occurred on topographic spurs within the escarpment and were less likely to have a runout extending to the escarpment base. The topography of the escarpment is not deeply incised, rather characterised by shallow and relatively open gullies, drainage features and spurs which resulted in minimal debris flow confinement. Key preparatory factors likely to have contributed to the failures include cementation of the sands susceptible to dissolution and lenses and layers of fine grained composition acting as aquicludes (multiple occurrences and anecdotal evidence of groundwater emanating from the zone of depletion).

Figure 3: Examples of landslides which occurred on the main escarpment in Muriwai

Generally, much smaller in volume than Muriwai, the landslides in Piha and Karekare were widely distributed, rarely clustered. With no distinct correlation with regards to source location, they typically initiated on slopes >25°. The critical preparatory factors considered is the permeability contrast between the shallow soil profile (typically residual soils and colluvium) and the underlying rock mass and the relatively steep dip of the rock surface on which the soils lie. As a reflection of the topography, the degree of confinement varied significantly with runout distances up to 1 km mapped where landslides entered incised gully features (Figure 4).



(a) (b)

(c) (d)

Figure 4: (a) Example of confined landslide in Piha with a runout extent over 1km. (b) Examples of landslides terminating on build infrastructure in Piha. (c) Example of landslide amalgamation at Marine Parade South in Piha. (d) Mapped landslides at the same location. Illustrating difficulty when differentiating separate debris flow runouts

In addition to the morphology of the topography, landslide runout direction and distance was often influenced by other factors including the type and density of vegetation, the presence of the built environment in the runout path (Figure 4), the accumulation (entrainment of additional soil in the runout path or amalgamation with other debris flows) (Figure 4) or depletion (deposition of debris along the runout path or splitting of a single debris flows in different directions) of debris volume.

5 REVIEW OF EMIPIRCAL RUNOUT METHODS

The AGS (2007) guidelines highlight the importance of the ability to predict landslide runout distance and velocity to reliably determine the extent it will affect property and persons downslope. This involves understanding the slope characteristics, mechanism of failure and characteristics of the downhill path. The guidelines indicate the importance of established empirical methods such as Hunter and Fell (2002) and Corominas (1996) to estimate runout distance. Where empirical methods are used for travel distance predictions, much judgement is required and it is important to calibrate the methods with observed landslide behaviour in the study area to reduce uncertainty and improve accuracy in the prediction model.

Empirical runout models for natural landslides that rely on statistical geometric correlations have long been established as a useful tool for predicting the runout distance to inform landslide risk assessments. The earliest empirical runout relationship was developed by Heim (1932) who proposed that the distance a landslide travels is proportional to its fall height defining the "Fahrböschung" angle (F-angle) as the tangent of the ratio of fall height (H) to horizontal runout distance (L) between the crest of the source zone and the toe of the deposit (Figure 5).

A number of authors have since expanded upon Heim's work, adopting an inverse correlation between landslide volume and Fahrböschung angle (Scheidegger 1973; Li 1983; Corominas 1996; Finlay et al 1999; Hunter and Fell 2002). These authors have also incorporated other variable factors such as path morphology, landslide classification, and obstructions in attempt to improve the Fahrböschung-volume correlation for more site specific adaptation. Hungr et al (2005) provides a concise overview of some these established methods, highlighting a lack of agreement among researchers with respect to volume for both large landslides (Hsü 1975) and small landslides (Hunter & Fell 2003) as a predictor for landslide mobility.

Corominas (1996) studied the effect of deflection, confinement and vegetation as obstacles for different landslide classifications. Dividing events into more homogeneous groupings produced distinct trends (although required the subdivision of an already small data set).

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, hypothesising that at low volumes, other factors like slope angle, path confinement, geology, groundwater, and failure mechanism have more of an effect on runout than at larger volumes, as small landslides do not develop the large energy/momentum that overshadows these factors.

Hunter & Fell (2002) revised previous work using more selective good quality data. Interestingly, they found significant improvement in their predictive models for travel distance angle (F-angle) by including the downslope angle below the source area (Figure 5). This applied to "rapid" slides on steep natural slopes. The downslope angle is defined as the average angle of the portion of the downslope from the landslide source area to the point where the slope begins to flatten out (Hunter & Fell, 2002).

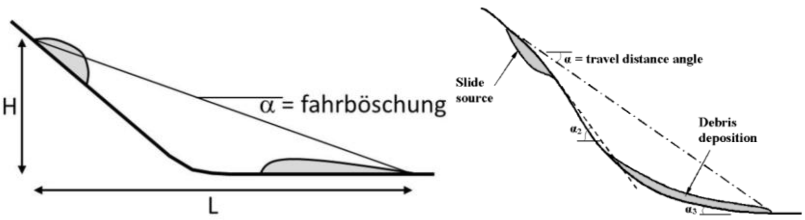


Figure 5: (Left) Fahrböschung angle definition, where H is the elevation difference between the source zone crest and toe of the runout and L is the plan distance between the source zone crest and toe of runout (after Heim, 1932). (Right) Definition of downslope angle below source area α_2 for slides on steep natural slopes (after Hunter & Fell, 2002)

More recent work by Brideau et al. (2021) using the correlation between landslide volume and Fahrböschung angle compiled a large dataset from previous published work (i.e. Scheidegger 1973; Li 1983; Corominas 1996) in combination with unpublished New Zealand landslides triggered by earthquakes and rainstorm events. They separated a series of plots for different landslide types, glacier versus unglaciated environments, travel path morphology and triggers (earthquake or rain). Clear variability in the data was evident, attributed to a range of site-specific and analysis specific conditions.

Other established methods include the correlation based on Galileo scaling laws, between landslide volume and the area covered by the deposit, which has been documented for rock avalanches and lahars (e.g. Li 1983, Iverson et al 1998). Whitall (2020) found good correlation with a length versus height relationship favourable for small open pit failures with small volumes at bench scale and showed that mobility of pit slope failures appear relatively insensitive to volume up to approximately 10,000 m^3.

6 EMPIRICAL RUNOUT ASSESSMENT USING CASE STUDY DATA

An inventory comprising 160 mapped landslides (32 in Muriwai and 128 in Piha and Karekare) formed the dataset used to develop empirical-statistical relationships between the H/L ratio and both landslide volume and downslope angle (Figure 6 and 7). Given the contrasting geomorphological and geological conditions at Muriwai compared to Piha and Karekare, the data was separated for the analysis. The data within each study area was divided into subsets for multiple linear regression analyses based on the influence of path morphology (degree of confinement) on the runout distance. At Muriwai three subsets were used; unconfined (slopes with little to no confinement), partially confined (landslide may enter a topographic drainage feature which has some influence on direction of travel) and confined (landslide typically entered a distinct gully / drainage feature, becoming channelised). At Piha and Karekare a simpler approach was adopted in an attempt to reduce ambiguity in the risk assessment process, two subsets were defined (unconfined and confined).

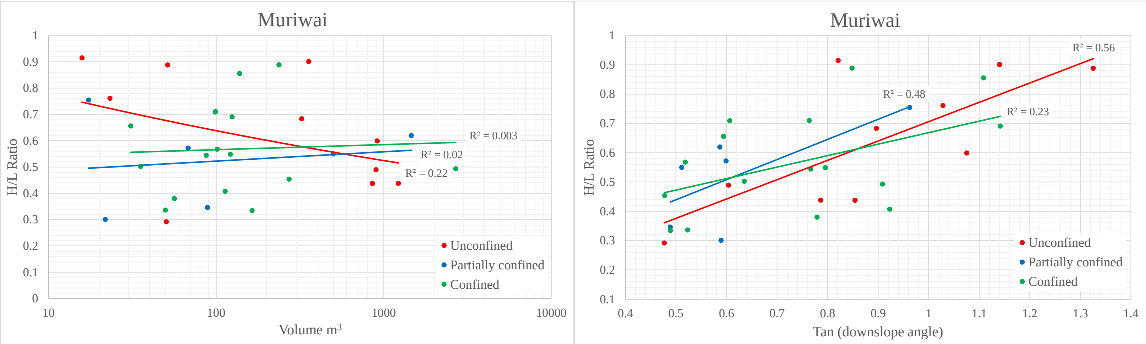


Figure 6: Empirical relationships for Muriwai landslides with different travel path morphologies for (left) H/L ratio and volume and (right) H/L ratio and downslope angle

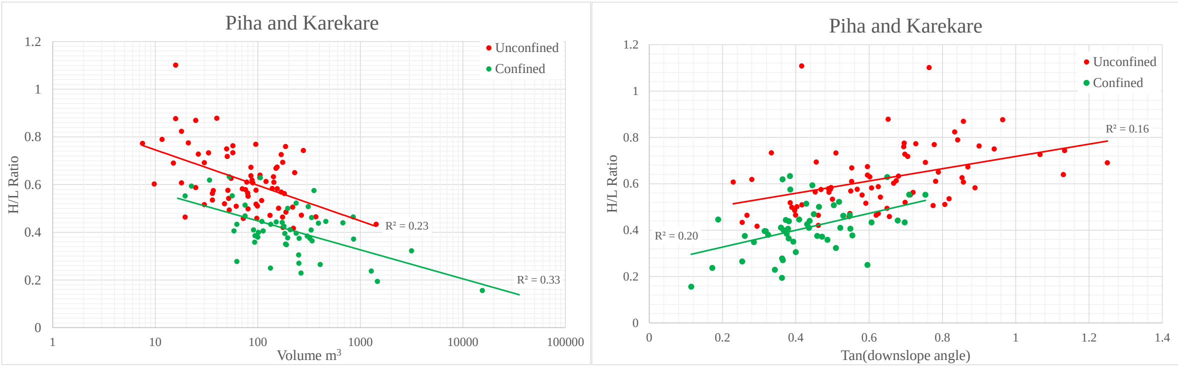


Figure 7: Empirical relationships for Piha and Karekare landslides with different travel path morphologies for (left) H/L ratio and volume and (right) H/L ratio and downslope angle

Interestingly the relationship between landslide volume and runout distance for the Muriwai data shows a broad scatter of data with a poor correlation between the H/L ratio and landslide volume. Adopting volume as the main variable, the most common empirical relationship in the published literature to predict landslide runout, did not appear useful in the case of Muriwai. The Hunter and Fell (2002) predictive method for "rapid" landslides on steep natural slopes in dilative soils correlates H/L with the downslope angle and degree of confinement. Using this method, the Muriwai landslide data shows a stronger correlation. The 'partially confined' travel path in particular was found to be very similar to the respective Hunter and Fell (2002) regression line (Figure 8). A comparison exercise of this method with the measured F-angles for several of the February 2023 landslides typically found agreement within a few degrees.

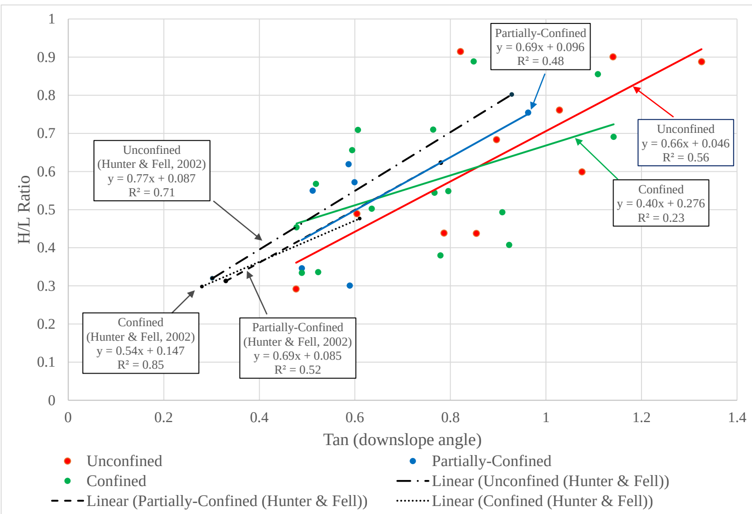


Figure 8: H/L ratio versus downslope angle relationship for Muriwai data together with Hunter & Fell (2002) relationships for rapid landslides on steep natural slopes in dilative soils.

The Piha and Karekare data show a clearer trend of reducing H/L with increased volume. It also demonstrates the dominant influence the degree of confinement had on the landslide runout behaviour for the February 2023 landslides.

The coefficient of determination R^2, for the best fit regression lines is 0.23 and 0.33 for unconfined and confined flows, respectively which can be considered 'weak to moderate' correlations. As a comparison, the data is also presented on a H/L ratio versus the tangent of the downslope angle and regression lines established. While there appears to be a correlation, there is a broader degree of scatter in the data relative to the relationship with volume.

7 RAPID LANDSLIDE RISK ASSESSMENTS

As part of the immediate emergency response there was a requirement for Auckland Council to make rapid decisions with regards to which homes were at risk from further landslide hazards and therefore required evacuation. The use of the Fahrböschung (F) angle was adopted by measuring runout distances of seven landslides, mapping the minimum and maximum F-angles from the crest of the escarpment across the remainder of the affected downslope areas (Roberts, 2024) (Figure 9). The results ranged from 22° to 25°. Each home was subsequently assigned a placard. The assessment is a good example of the effectiveness of the F-angle approach as an initial screening tool, but was not intended for use in longer term decision making or planning (i.e. adoption in the quantitative landslide risk assessment process).

Ultimately, in the case of Muriwai, the landslide risk assessment process was guided by a computer simulated three-dimensional debris flow assessment (RAMMS software) which estimated the landslide runout behaviour of future landslide hazards initiating from the escarpment crest (Figure 9).The modelling process took nearly six months and therefore the use of empirical-statistical relationships established between H/L ratio and downslope angle for predicting landslide runout was adopted as an interim method where rapid decision-making was required. Empirical methods were also used to further verify the RAMMS modelling outputs and the observed landslide runouts.

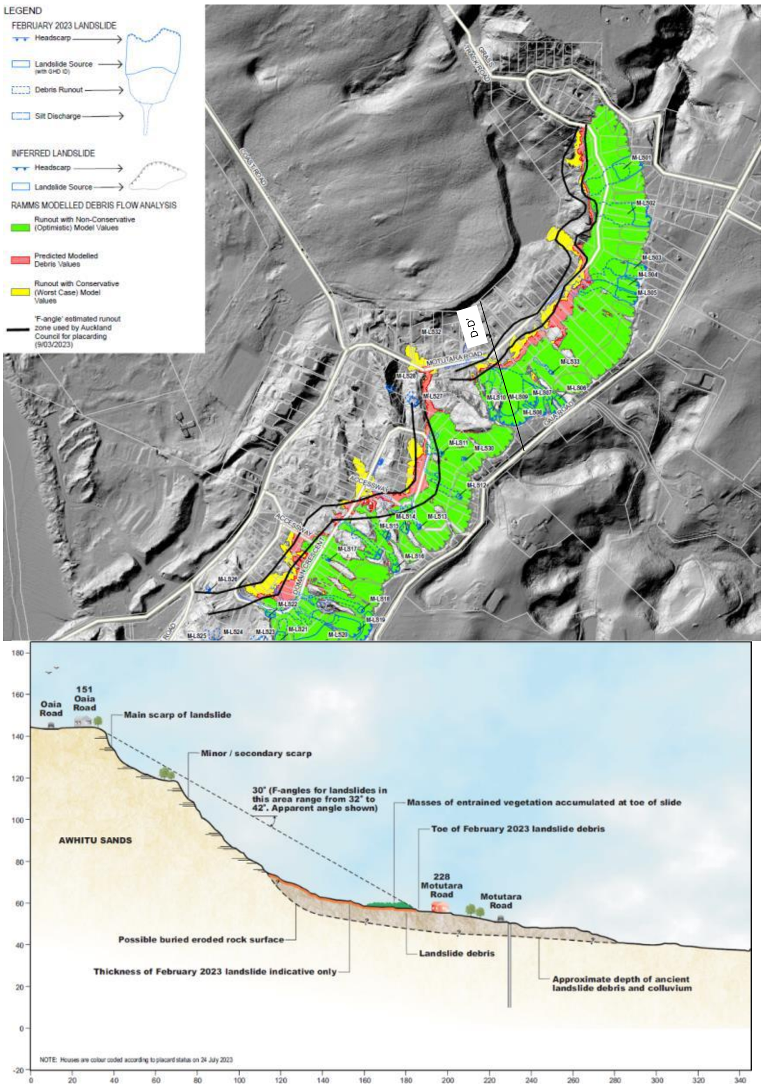


Figure 9: (Top) Results of RAMMS modelling showing simulated debris flow extents in Muriwai and best and worst case F-angles (black lines). (Bottom) Illustrative cross section (D-D') showing F-angle measurement.

The use of numerical analyses were considered inappropriate for Piha and Karekare due to both time constraints and the dispersed nature of the sites requiring assessment. Therefore, the development of empirical-statistical relationships formed an integral element of the risk assessment process. The probability of spatial impact $P_{(S:H)}$ was partitioned into two separate conditional probabilities,

$$P_{(S:H)} = P_{(S':H'2)(H)} x \, P_{(S':H'2)} \qquad (2)$$

Where,

$P_{(S':H'1)}$ is the probability that if the landslide occurs it travels in the direction of the site under assessment

$P_{(S':H'2)}$ is the probability that is the landslide occurs it will travel to at least the site under assessment and will impact the property.

Given the understanding that the direction of debris flow runout is typically determined by the nature of the slope morphology below the source area, a rapid method for predicting flow direction was required. Flow accumulation analysis was completed using the 2023 DEM. This is a GIS tool typically used for hydrological modelling and deriving accumulated flow from a DEM. Assuming a landslide source area (typically slopes >25° above the site under assessment), the tool provided a rapid solution to determine the potential direction a landslide would travel (Figure 10). If the slopes are generally unconfined a landslide is assumed to travel perpendicular to the contours i.e. straight down the slope towards the site under assessment, a high probability of 0.8 to 1.0 was adopted. If debris is likely to become channelised (confined) by entering a topographic feature, and the site is within the down slope path of the channel, a probability of 0.8 to 1.0 was adopted. Where the channel is likely to direct the landslide away from the site, a low probability of 0.05 was adopted. The flow accumulation analysis was also used to help determine whether the potential landslide hazard would be defined as unconfined or confined for the purposes of assessing travel distance.

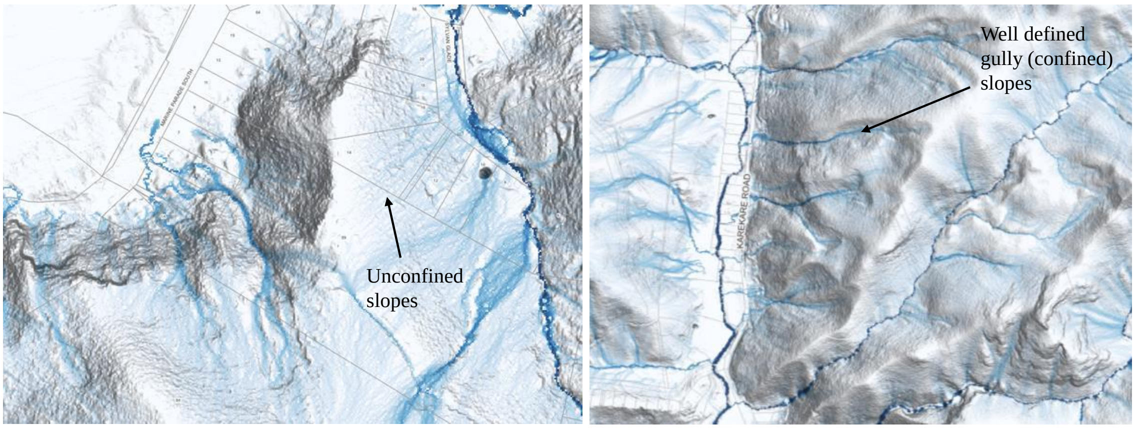


Figure 10: Examples of flow accumulation analysis used as a rapid tool to predict the likely behaviour of debris flows occurring above the sites. (Left) Unconfined slopes. (Right) Landslides likely to become channelised in gully features (confined)

To estimate the volume of a future landslide hazard which could be consistently applied to each site under assessment, a 'most likely significant landslide' definition was adopted. This was determined by analysing the range of February 2023 landslide volumes in combination with the respective level of damage inflicted. It was found that once the volume reached approximately 100 m^3, most debris flows resulted in partial or complete collapse of a building. To predict the landslide travel distance, the corresponding F-angle for either unconfined or confined flow was determined using the best fit linear regression line on the H/L ratio versus volume plot. The F-angle was transposed onto a cross section from the assumed landslide source through the predicted travel path and site under assessment and landslide runout extent determined by its intersection with the topography. A probability of 1.0 was adopted where the F-angle projected beyond the building, 0.5 where it projected to the rear of the building and 0.0001 where it fell short of the building. Noting that observational behaviour took precedence where relevant i.e. if a previous landslide within close proximity to the site travelled further than predicted runout, a greater travel distance was assumed.

A particular site within Piha worthy of discussion is North Piha Road. A number of properties requiring a landslide risk assessment located along the backshore of Piha beach lie at the base of an escarpment on which six landslides occurred during the February 2023 event. Both empirical and numerical approaches were adopted to compare the predicted runout of future landslide hazards occurring above 35 properties. A series of section lines were produced along the escarpment and the F-angle projection lines applied (Figure 11). A numerical analysis utilising DHI's proprietary software MIKE Zero 2023, typically used to model surface water flow, and similar to RAMMS, simulated debris flows incorporating material parameters based on the behaviour of landslides in the previous event. A reasonably good correlation was found between the predicted landslide runout extent for both the empirical and 3D modelling approaches (Figure 11). Judgement was weighted towards evidenced based behaviour of previous landslides where significant discrepancy was observed.

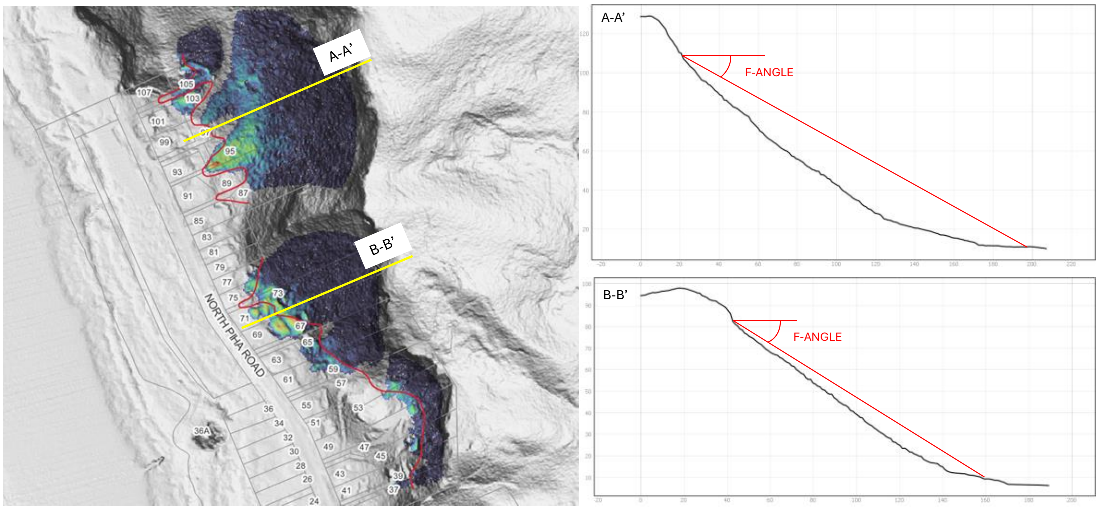


Figure 11: (Left) Modelled debris flow runout extents using MIKE Zero 2023 and estimate extent based on F-angle modelling (red line). (Right) Examples of F-angle transposed onto cross section through two sites

The approach of selecting a single value from the best fit regression lines on the H/L ratio versus volume plot proved effective for this assessment. The AGS (2007) guidelines, and others (i.e. McDougall, 2017) suggest a probabilistic approach could be used to limit uncertainty by defining the probability of exceedance of a specific landslide volume. Alternatively, the level of uncertainty in the dataset could be accounted for by using confidence intervals. Figure 12 shows the lower bound 50% confidence interval for unconfined and confined flows, i.e. where in 50% of cases, the true average H/L ratio will fall within this range. As a result, a more conservative approach, given the scatter of data could be to adopt the H/L ratio corresponding to this lower bound line.

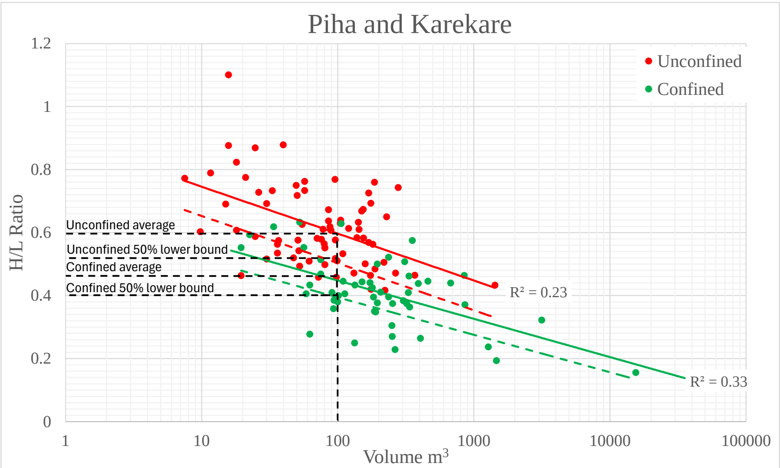


Figure 12: Empirical relationship between volume and H/L for Piha and Karekare data showing lower bound 50% confidence intervals

8 DISCUSSION

The adoption of well-established empirical-statistical methods for predicting landslide runout proved to be a highly effective approach in supporting the rapid delivery of area-wide landslide risk assessments in Muriwai, Karekare, and Piha. This success was largely driven by the early development of an extensive landslide inventory, similarities in landslide classification within each study area and the recognition of the role that downhill morphology played in controlling both landslide direction and reach.

To enhance the accuracy of spatial impact probability for the Piha and Karekare study areas, the probability was partitioned to account for both travel direction and distance. Combing the empirical-statistical models with simple flow accumulation modelling proved particularly valuable. The assessment methods developed were relatively systematic and straightforward to apply, which was crucial given the variable site-by-site topographic conditions, the number of practitioners utilising them and the paucity of time under which assessments had to be made. Developing a standardized approach early on in the process including the probability values to be applied to given conditions ensured consistency in risk assessment outcomes across different locations. Additionally, the importance of applying judgment when allocating probabilities based on observed behavior from the event was evident. While empirical models were very informative, judgement of the results was necessary to account for site-specific nuances and uncertainty.

Variability in observational landslide runout data introduced significant scatter to the empirical-statistical models, particularly between the two study areas. The general scatter reflects uncertainty in the adopted F-angles when predicting landslide runout distance. A more conservative approach to capturing this uncertainty in future assessments could be to plot the probability of exceedance or confidence intervals and select predicted values accordingly. Several site-specific factors have been postulated for the contrasting H/L and volume correlations between the Muriwai and Piha and Karekare data:

- The effect that source material properties may have on debris flow behaviour. Muriwai are soils dominantly sandy whereas the Piha and Karekare material were fine grained soils.
- In many instances at Muriwai it was difficult to differentiate between debris flows due to the amalgamation. Therefore, the measured runout extents do not reflect their true behaviour.

The variability in the general dataset could be attributed to a number of influencing factors which might include:

- The impact of the built environment, such as driveways, buildings and roads, which often resulted in extended or reduced travel distances.
- The accumulation or depletion of debris along the runout path (including amalgamation or splitting of flows), which altered the overall volume of material.
- The type and density of vegetation within the runout path.
- Successive landslides originating from the same or adjacent source areas in the days or weeks after the initial event, leading to combined flows, resulting in extended runouts. This reflects the importance of early reconnaissance following the event.
- A relatively narrow range of volumes in the dataset, leading to weaker correlation strength within the predictive models.

Numerical methods proved useful in both Muriwai and North Piha and the results of these assessments appeared to show reasonably good correlation with the empirical-statistical predictive models. Several authors have provided comprehensive comparisons between empirical-statistical methods and numerical methods that rely on process based modelling (McDougall 2017, Brideau et al 2021, Komu et al 2022) but a summary of some key lessons from this study include:

- Empirical-statistical methods are a simple but powerful tool for both initial screening and adoption in the quantitative assessment where a sufficient dataset is established using past landslide events, but it is important to reflect uncertainty in the predictions.
- The appropriate published correlation needs to be adopted, and the recognition and incorporation of site specific variable factors is critical to produce an effective prediction model.
- Empirical-statistical runout models should be complimented with other additional yet simple tools where possible, particularly where there is ambiguity with respect to landslide direction or the degree of confinement.
- Evidenced based observational behaviour is essential, and should often take precedent when applying judgement to the selection probability values
- Numerical runout methods can provide detailed runout models providing useful outputs such as debris thickness and velocity. They rely on calibration with accurate observations of previous site specific landslides.
- RAMMS modelling worked well for Muriwai but took several months. However, RAMMS modelling could not be calibrated with the recorded landslide data in North Piha and therefore the selection of software applicable to the site and data is important.

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