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LANDSLIDE VULNERABILITY: LEARNINGS FROM THE IMPACTS OF DEBRIS FLOWS ON BUILDINGS TO INFORM QUANTITATIVE LOSS OF LIFE RISK ASSESSMENTS

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ABSTRACT

A significant weather event in February 2023 triggered numerous landslides in the townships of Muriwai, Piha and Karekare in the Waitākere area on Auckland's West Coast. The event caused widespread damage to residential buildings and resulted in two deaths. Most landslides materialised as debris flows. Due to their high velocity and ability to travel long distances, debris flows pose a significant risk to life. Vulnerability can be described as the conditional probability of death (given a landslide impact), or as a conceptual measure of overall human susceptibility, sensitivity or proneness to landslide hazards (human vulnerability). The former is often related to the collapse of occupied buildings and thus is indirectly, a function of structural vulnerability.

This case study found the extent and nature of damage to residential buildings, and therefore vulnerability of the occupants, varied considerably. Typically, extent of damage depended on debris flow volume, and the recency of construction of the building. Building collapse due to inundation was common, however other 'atypical' instances of damage included buildings being 'rafted' downslope and the occupants escaping unharmed, trees entrained in the top of the debris penetrating the upslope side of buildings, buildings being undermined and remaining intact, and significant volumes of debris resting against the upslope wall but resulting in minimal, if any, damage. This variability indicates there can be significant uncertainty in the outcome of a landslide risk assessment, which can be difficult to quantify.

AGS (2007c) includes a table of example vulnerability values for a limited number of inundation and building damage scenarios, adapted from Finlay et al. (1999). In some instances, there are wide ranges in the data and a practitioner must use judgement to select an appropriate value. Should the building collapse, which occurred with many of the buildings impacted by landslides in Muriwai, Karekare and Piha, AGS (2007c) recommends a value of 1 (death is almost certain) be adopted. A revised and expanded set of vulnerability values adopted for the study site is presented in this paper.

Human behaviour is a key factor of human vulnerability (Pollock & Wartman, 2020) and had a large influence on the resulting number of deaths as many residences that suffered significant damage were either unoccupied or evacuated. Had this not been the case, the survivability in many properties would likely have been low. Records of human behaviour are often poorly persevered during an event (Pollock & Wartman, 2020), and it is difficult to predict the influence of human behaviour in a risk assessment. As such, human behaviour is generally ignored during the risk assessment process in favour of the worst-case scenario approach.

1 INTRODUCTION

1.1 WAITĀKERE LANDSLIDE EVENTS

Two significant weather events in January and February 2023 were the result of ex-tropical cyclone Hale and Gabrielle, respectively. As a consequence of these weather events, Auckland experienced its wettest period since records began, accumulating over 45% of its average, annual rainfall in approximately one month (Fowler, 2023). Following cyclone Gabrielle an already saturated Auckland experienced catastrophic flooding and slope instability. One of Auckland's worst affected regions was the Waitākere Ranges.

The Waitākere Ranges are a chain of hills located along Auckland's West Coast, approximately 25 km long (north to south) and approximately 25 km to the west of central Auckland. The ranges are comprised of various volcanic sequences which originate from the flanks of the Waitākere Volcano, the centre of which is located approximately 200 km offshore and is approximately 15 – 25 million years old. These sequences were uplifted approximately 3 – 5 mya and generally contain volcanoclastic conglomerates, ash and igneous intrusions (Hayward, 1979). The Waitākere Ranges are home to smaller, generally coastal, settlements in discrete locations along the length of the ranges.

As a function of the early 2023 rainfall events, resultant land instability observed in the Waitākere Ranges was generally expressed as debris flows and avalanches (which included rocks, trees, and other vegetation), and to a lesser extent rockfalls. Many of the debris avalanches became saturated debris flows as they travelled downslope. These flows resulted in significant damage to buildings and infrastructure. Tragically, two fatalities occurred as a result of debris flow impacts on private dwellings in Muriwai. A similar storm event in Muriwai in 1965 also claimed two lives. Fortunately, early warning weather systems had predicted the February 2023 storm, which meant that many inhabitants of affected areas had evacuated their houses prior to the ensuing instability, following directions from local and regional authorities. Figure 1 presents an example of typical damage observed in the aftermath of the event.

Figure 1: Complete destruction of a dwelling in Muriwai resulting from debris flow impact.

1.2 POST-LANDSLIDE RISK ASSESSMENT PROCESS

Immediately following the landslide event, rapid building assessment of residential buildings was undertaken by Auckland Council. This system utilised a "traffic light" approach allowing Auckland Council building inspectors to classify buildings as white (unrestricted access), yellow (temporary or partially restricted access), and red (no access permitted). These rapid building assessments were intended as a preliminary assessment of risk to occupants, as a function of the buildings damage and/or its perceived risk of further damage at the time.

Following the rapid building assessments, Auckland Council commissioned GHD to undertake loss of life landslide risk assessments on more than 100 properties over a 7-month period. Properties of the worst affected Waitākere settlements of Muriwai, Piha, and Karekare were assessed as part of this work. The risk assessments were to be conducted as quantitative, loss of life assessments in accordance with the Australian Geomechanics Society, Guidelines for Landslide Risk Assessment and Management, 2007 (AGS, 2007).

1.3 VULNERABILITY TO LANDSLIDES

The term "vulnerability" as used in this paper and in the referenced literature has different contextual definitions. This paper explores vulnerability in the dual context of the following:

- Vulnerability as a "specific conditional probability" within the context of a calculation of the probability of loss of life assuming impact from a landslide, as defined by AGS (2007c), and
- Human Vulnerability to landslides when used as a measure of overall susceptibility, sensitivity or proneness to landslide hazards. In this context, human vulnerability includes overall considerations of spatial and temporal factors, the degree of injury or impact and interplay of human behaviour on the potential outcome for the possible occurrence of a hazard.

This paper intends to document observations from Waitākere following the Cyclone Gabrielle weather event and how these observations may inform both the conditional probability related to vulnerability of the occupants of effected houses and the overall concepts of human vulnerability.

2 AGS 2007 GUIDELINES FOR LANDSLIDE RISK ASSESSMENT AND THE ROLE OF VULNERABILITY AS A CONDITIONAL PROBABILITY TERM

2.1 SUMMARY OF THE GUIDELINES

The AGS 2007 Guidelines for Risk Assessment and Management are a landslide risk management (LRM) framework to assess (i.e. evaluate hazard and consequence against a tolerance criteria) and manage (i.e. mitigation, land use planning, etc.) the risk posed by landslides to properties and persons.

Risk assessments can be performed qualitatively or quantitively. Qualitative assessments are an assessment of likelihood and consequence using prescribed outcome descriptors and values that correspond to specified probability descriptors. Generally, this method is useful for assessments that require repeatability, however, they can be restrictive as the assessor is limited to the outcomes or possibilities as prescribed by the descriptors. It is generally accepted that qualitative risk assessments are not sufficient for the assessment of loss of life risk, due to the difficulties of incorporating conditional probabilities (such as spatial and temporal probability) into a likelihood and consequence matrix. As such, AGS requires that 'loss of life' risk assessments are to be estimated quantitatively.

Quantitative assessments are numerical assessments where each element of the assessment is assigned a probability between 0 (not occurring) and 1 (definitively occurring). Quantitative assessments are useful as they can be adapted for scenarios that are not specified by generic qualitative descriptors and allow for direct comparison with tolerable 'loss of life' risk criteria. However, it must be recognised that quantitative risk assessments have an inherent level of uncertainty which is not usually implicitly stated. The equation for quantitatively calculating the risk of loss of life is defined by AGS (2007) as follows.

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

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).

Although it is the responsibility of the managing authority to determine what is ultimately deemed a 'tolerable risk', the AGS guidelines present suggested tolerable loss of life risks for the person most at risk (Table 1). Acceptable risks are usually considered to be one order of magnitude lower than tolerable risks.

Table 1: AGS suggested tolerable loss of life individual risk.

Situation	Suggested Tolerable Loss of Life Risk for the Person Most at Risk
Existing slope (1) / Existing Development (2)	10^{-4} / annum
New Constructed Slope (3) / New Development (4) / Existing Landslide (5)	10^{-5} / annum

2.2 VULNERABILITY TO THE INDIVIDUAL

Establishing the vulnerability to an individual can be highly subjective. This is because vulnerability is generally assessed empirically using published information or, if an event is large enough, proxies from the same event.

Vulnerability is described in the AGS guidelines as: "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.". For a person, this is essentially asking: if the landslide occurs, travels in the direction of the person most at risk, reaches their location, and they are present at the time of impact, what is the probability that they will die? Collecting data with respect to the vulnerability of an individual in the aftermath of a catastrophic event is challenging, as such, vulnerability is generally expressed as a function of structural vulnerability as this data is more readily available and measurable following an event. The influence structural vulnerability has on the vulnerability of an individual is reflected in the table of vulnerability values for various inundation and building damage scenarios as adapted by Finlay et al. (1999) presented in AGS (2007).

Table 2: Vulnerability values from Finlay et al. (1999).

Case	Range in data	Recommended value	Comments
Person in open space			
If struck by a rockfall.	0.1 – 0.7	0.5	May be injured but unlikely to cause death.
If buried by debris.	0.8 – 1.0	1.0	Death by asphyxia almost certain.
If not buried.	0.1 – 0.5	0.1	High chance of survival.
Persons in a vehicle			
If the vehicle is buried/crushed.	0.9 – 1.0	1.0	Death is almost certain.
If the vehicle is damaged only.	0 – 0.3	0.3	High chance of survival.
Person in a building			
If the building collapses.	0.9 – 1.0	1.0	Death is almost certain.
If the building is inundated with debris and the person is buried.	0.8 – 1.0	1.0	Death is highly likely.
If the debris strikes the building only.	0 – 0.1	0.05	Very high chance of survival.

3 PUBLISHED INFORMATION ON OVERALL HUMAN VULNERABILITY

3.1 DEFINING HUMAN VULNERABILITY

Human vulnerability is often discussed as the conceptual susceptibility of people to landslides and is generally considered to be a function of both structural vulnerability and human behaviour. The factors influencing human vulnerability can affect the spatial ($\mathbf{P}_{(S:H)}$) and temporal ($\mathbf{P}_{(T:S)}$) probabilities, as well as the vulnerability ($\mathbf{V}_{(D:T)}$). Discussion on structural vulnerability and human behaviour from relevant literature is presented in the following sections.

3.2 STRUCTURAL VULNERABILITY

3.2.1 Factors influencing structural vulnerability

Structural vulnerability (sometimes termed physical vulnerability) at its simplest, is a function of the construction material, type of landslide, velocity of the landslide, and impact pressure of the landslide. However, other factors such as, height of the building, size of the building, number of floors, age of the building, location of openings, and type of foundation can also impact the structural vulnerability (Papathoma-Köhle et al., 2017). Kang & Kim (2015) derives relationships for structural vulnerability from inundation depth, flow velocity and impact pressure, for both non-concrete and reinforced concrete framed buildings, presented in Figure 2.

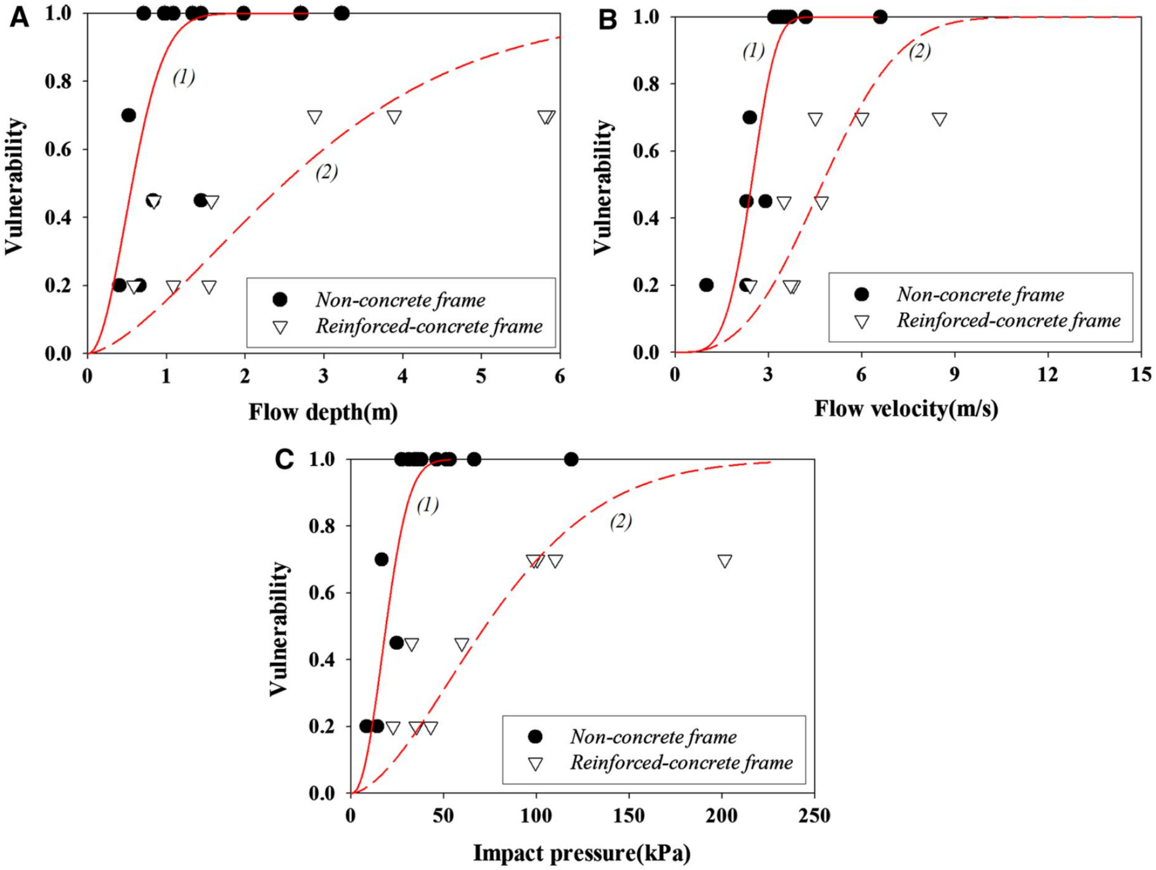

Figure 2: Graphs of vulnerability against flow depth (A), flow velocity (B), and impact pressure (C) from Kang & Kim (2015).

3.2.2 Damage of different building types

As indicated by Kang et al. (2015), timber framed buildings (non-concrete framed buildings) generally have less resistance to landslide damage resulting from debris flows or rockfalls than masonry or concrete structures. A study of debris flows in Korea by Kang and Kim (2015) indicates that for timber framed buildings, complete building collapse can be the result of debris heights between 0.97 - 3.89 m. Massey et al. (2018) determined that for timber framed buildings collapse occurred at flow depths of about 1.4 - 1.6 m. Pollock & Wartman (2020) determined that for most structures (including concrete framed buildings), inundation greater than 2.5 m resulted in complete building collapse regardless of building material type. Based on this, one could infer that inhabitants of concrete framed buildings are likely to have lower vulnerability than those living in timber or other less rigid material-type structures. However, as Pollock & Wartman (2020) points out, the structural resilience of rigid materials may be both a blessing and a curse. Although debris may exert less damage on rigid structures at low and moderate inundation depths, if the debris intrudes into the building through structurally weak areas such as windows and doors, debris may fill the building rather than exiting, thus trapping and burying the occupants. Pollock & Wartman also concluded that at inundation depths capable of collapsing buildings regardless of construction material, falling masonry or concrete slabs may be more deadly than the landslide itself.

Massey et al. (2018) collated structural damage assessments resulting from debris flows including data sets from Italy, Austria, South Korea, Hong Kong, Spain, Switzerland, and New Zealand. The resulting damage ratio to debris height graph is presented in Figure 3. Although a generally increasing trend with debris height was noted for the damage ratio, there was still much variability in the data with an instance of a 3.0 m debris height resulting in a damage ratio of 0.15, and an instance of a 1.15 m debris height resulting in a 1.0 damage ratio. This speaks to the variability of outcome when assessing a structures vulnerability, and the need to consider other factors for example, debris flow velocity and foundation type.

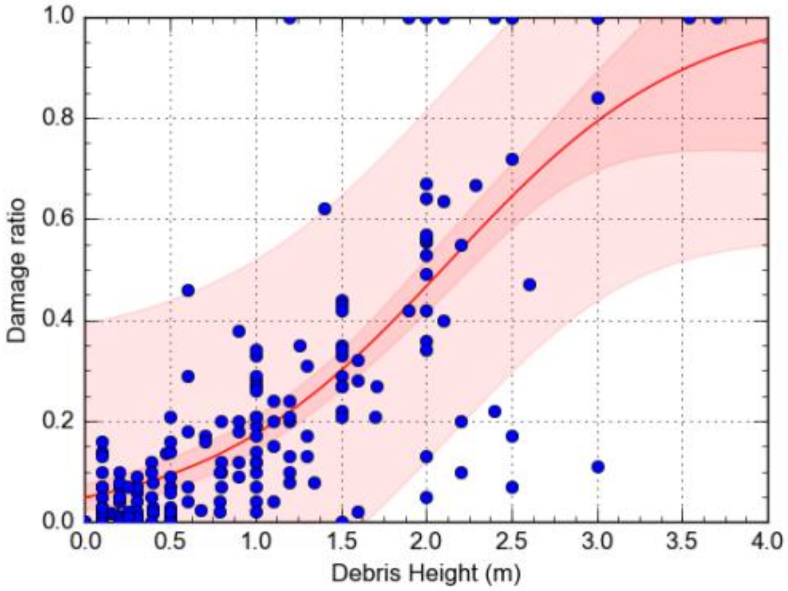

Figure 3: Damage ratio vs debris height from Massey et al. (2018).

3.3 HUMAN VULNERABILITY

3.3.1 Influence of human behaviour

While still considered to be related, the interplay between structural vulnerability and human vulnerability is generally not considered to be a direct relationship (Pollock & Wartman, 2020). This is likely due to inherent differences in coping potential between individuals and the ability of humans to act to dynamically to change their vulnerability (Crozier & Glade, 2005). The effect that dynamically reacting to a situation had on human vulnerability was investigated by Pollock & Wartman (2020). Conclusions drawn from this study indicated that awareness of an approaching threat, even if its location and nature were unknown, sharply decreased the odds of death, with those who were not aware eight times more likely to be killed. Of those who were able to identify a threat, actions taken included moving away from the perceived direction of the threat, escaping vertically to a higher floor or the top of furniture, or sheltering in a prepared refuge area in their home. Those who took no protective action were five times more likely to be killed. The survival rate of individuals on the second or third floors, including attics and roofs, was 95%, with those on the ground floor 12 times more likely to be killed.

Pollock & Wartman (2020) also documents the socioeconomic component to human vulnerability. They concluded that economically developing nations have significantly greater human vulnerability than developed nations at almost all inundation depths. In their study individuals in developing nations had six times the likelihood of death of those in developed nations.

3.3.2 Building inundation and occupant causes of death

Pollock & Wartman (2020) indicates that there is a mild correlation between human vulnerability and inundation depth. Additionally, they go on to state that the greatest increase in probability of death is observed between 0 and 2 m, although no fatalities are recorded below inundation depths of 0.8 m, likely due to the intrusion of debris into buildings through structural weak points such as windows, commonly set at heights of ~1 m, after which debris may overwhelm and bury occupants (Massey et al., 2018; Totschnig et al., 2011). Despite this, the maximum building inundation depth survived by an individual in the study was 9.6 m, the victim survived with severe injuries. Given this, Pollock & Wartman concluded that at intermediate inundation depths, human behaviour is the most significant factor in landslide mortality. The main causes of death from landslide impacts are traumatic injury and asphyxiation generally as a result of burial or physical impacts from the landslide or building (Pollock & Wartman, 2020; Massey et al., 2018).

4 OBSERVATIONS OF BUILDING DAMAGE IN THE WAITĀKERE LANDSLIDE EVENTS

4.1 INUNDATION FROM DEBRIS FLOWS

The settlements of Muriwai, Piha, and Karekare were initially established prior to 1940 with residential development becoming more widespread through the mid to late 1900s. New Zealand's building code came into effect in 1992 after the passing of the Building Act in 1991 which was repealed and replaced in 2004. Many dwellings constructed before the introduction of the Building Act and Code still exist today. The majority of dwellings constructed before the year 2000 are timber framed with light weight cladding, whereas in recent years concrete has become an increasingly favoured building material. This difference in age of the dwelling and material type produces a stark contrast in the ability of a dwelling to withstand the effects of inundation.

Observations of many dwellings effected by landslides indicated that generally, debris flow heights of between 0.5 – 1.0 m resulted in the collapse of buildings. However, some atypical instances of inundation were also observed. These included recently constructed (concrete framed) buildings that were able to withstand larger volumes of inundation (>5 m), including large volumes of debris resting against the upslope side of dwellings resulting in minimal damage (Figure 4). In these cases, while the dwellings remained mostly intact, debris often entered the dwellings through weak points such as windows and doors. Figure 5A presents an example of this where the same dwelling is encased in debris (visible through window in background of photo) and the debris has penetrated an upslope widow, depositing material in the living room.

Other examples of inundation not resulting in complete building collapse included dwellings where landslide debris (greater than 0.5 m in height) had entered a portion of the dwelling or had displaced a dwelling from its original location. The example presented in Figure 5B is a scenario where debris greater than 1.0 m in height, has entered the dwelling and the dwelling has not collapsed. This image highlights the variability in an individual's spatial probability ($\mathbf{P}_{(S:H)}$). If the occupant of the dwelling is in the kitchen (background of the photograph engulfed in debris) during the landslide event their spatial probability would almost certainly be 1.0, as they would be expected to be engulfed in the debris, likely resulting in a vulnerability ($\mathbf{V}_{(D:T)}$) of 1 also. However, if the occupant of the dwelling is in the living room (foreground of the photograph) at the time of the landslide event, their spatial probability might instead be somewhere between 0 – 0.5, given that they might only be slightly impacted by debris or not at all, likely resulting in a much lower or non-existent vulnerability. Additionally, the same is true in Figure 5A, considering a person sitting on the couch by the window adjacent to the debris would have a different vulnerability than a person sitting on a couch on the other side of the room.

Other atypical instances of inundation included dwellings being "rafted" downslope by multiple to tens of meters, and the dwellings remaining relatively intact (Figure 6A). Residents of Karekare confirmed that there was at least 1 instance of people occupying their house during the events, which was then picked up and "rafted" downslope by approximately 20 m. Once the dwelling came to rest it was mostly intact and the occupants were able to escape the dwelling physically unharmed. Figure 6B illustrates an example of a dwelling which has been rafted downslope by more than 10 m, and in doing so completely destroyed the lower-level, while the upper-level remains almost completely intact. In this example, the vulnerability of a person occupying the lower-level would likely be between 0.8 – 1.0, whereas a person who is occupying the upper-level is likely to have a significantly lower vulnerability of about 0.05 given the upper-level remained largely intact.

4.2 THE EFFECTS OF VEGETATION

Many of the slopes which failed during the events comprised a significant amount of vegetation. Vegetation type varied from small, dense shrubs to large, well established pine trees. While vegetation can have a stabilising effect on slopes, it was observed that this stabilising force was overcome by the force of the debris flow, resulting in vegetation becoming entrained within the debris, ultimately increasing the overall debris flow volume. The different effects vegetation had on dwellings within the project site included:

- Trees, shrubs and other vegetation becoming entrained within the landslide debris, subsequently increasing the volume of the debris impacting dwellings,
- Tall trees (in this case mainly pines) being carried downslope and penetrating the upslope side and roofs of dwellings (Figure 7).

4.3 THE IMPACTS OF ROCKFALL

Although rockfall hazards can pose a significant risk to dwelling occupants, there were limited instances of rockfall impacting dwellings during or following the landslide event. Given the geology of the area (volcanoclastic conglomerates, ash, and intrusions) headscarps formed by the landslides often exposed profiles of residual soil (which commonly included core stones) and weathered rock. Additionally, colluvium hung up on the slopes following the event usually contained large core stones. As a result of ongoing weathering and degradation of these exposed profiles and colluvium, the release of rocks from the failure areas resulted in rockfalls impacting close to dwellings. There were no observed instances of rockfalls causing death, injury or significant building damage.

4.4 UNDERMINING SCENARIOS

The regression of landslides below building platforms and building foundations was also observed. Damage from the undermining of a building varied and was ultimately dependant on how close to the building the landslide regressed, and the foundation system and material type of the building. Generally, flexible structures (such as light weight timber framed buildings) were able to withstand a significant agree of undermining, on the order of 3+ m (Figure 8), whereas rigid concrete framed structures were more susceptible to damage from undermining. However, quantifying the amount of undermining required to cause collapse proved difficult as no examples of complete building collapse resulting from undermining was observed. Given this, it was assessed that survivability is likely to be relatively high in an undermining scenario where the building does not completely collapse.

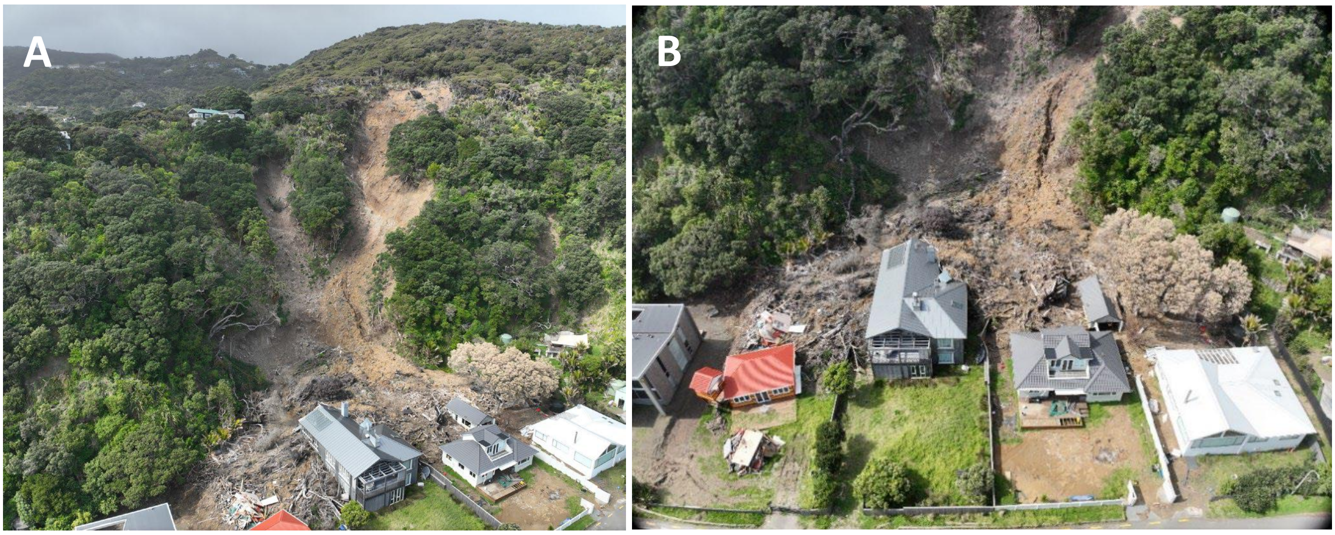

Figure 4: (A) Aerial photograph of a landslide and debris flow that has impacted several houses. Debris height is approximately 5-6 m behind the middle house. (B) Aerial photograph of dwellings affected by a large debris flow, showing older (pre-1970s construction) red, left house moved completely off foundations and grey middle house (post 2000s construction) remains in place.

Figure 5: (A) Landslide debris entering into the living room of dwelling by penetrating windows and wall. Dwelling is encased in debris as evidenced by debris visible through window in background. (B) Photograph of the inside of a dwelling which landslide debris has entered. In the background of the image, covered in debris, is the kitchen, the foreground contains the living room.

Figure 6: (A) Dwellings which have been rafted downslope from their original locations remaining relatively intact. (B) Photograph of a dwelling which has been rafted and toppled over by a landslide, with lower-level of the dwelling completely destroyed, while the upper-level remains mostly intact.

Figure 7: Photographs of a dwelling which has been impaled by a tall pine tree. Both photos are of the same dwelling taken at ground level and from the headscarp, respectively.

Figure 8: Photograph of a landslide undermining a timber framed dwelling. Leading edge of the dwelling is undermined by approximately 3 m.

5 DISCUSSION

5.1 OBSERVATIONS FROM WAITAKERE

5.1.1 Vulnerability as a conditional probability

The guidance presented in AGS (2007) for assessing the conditional probability term, vulnerability is limited and the adapted table from Finaly et al. (1999) presents vulnerability values for a limited range of scenarios. AGS (2007) also only provides guidance for vulnerability resulting from inundation, which is generally associated with debris flows. Other landslide mechanisms, such as rockfall or undermining from landslide regression, are either generic or not explicitly catered for. As such, adapted table(s) of vulnerability values incorporating available data, expert judgement and site-specific information are required to adequately cater for the observed instances of damage.

Given the large volume of properties requiring rapid risk assessments, a standardised approach to assessing the loss of life risk was created out of necessity. This involved standardising the assessment of vulnerability. As discussed above, the adapted table of vulnerability values presented in AGS (2007c), adapted by Finaly et al. (1999), did not adequately cater to the building damage scenarios observed in the field. Therefore, further adaptations of the table included combining it with information from the TfNSW Guide to Slope Risk Analysis (RMS, 2014) as well as observations of damage to buildings and structures resulting from the landslides in Muriwai, Piha, and Karekare. The table is presented as Table 3.

Published vulnerability data for rockfall events in New Zealand was poorly known at the time. Given this, and the fact that there were no observed instances of rockfall causing death, injury or damage to buildings, vulnerability values related to rockfall have not been included.

Table 3: Expanded set of vulnerability values for inundation and undermining scenarios.

Case	Range	Typical value used for Waitakere 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	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.

5.1.2 Human vulnerability

More recently published human vulnerability data is limited and biased towards human vulnerability as a function of structural vulnerability, given that human behaviour in an event is difficult to predict and measure. From the published literature it is clear that structural vulnerability varies considerably for each building and each scenario as each study presented in Section 3 concluded different debris heights resulted in complete building collapse. This misalignment is likely due to the variability in different material types, foundation types, building openings, building age, landslide volume, landslide speed and energy, etc. This uncertainty inherently requires an applied level of judgement and caution when applying these results to a given vulnerability assessment.

Pollock & Wartman (2020) indicates that human behaviour (including the ability to dynamically react to a situation, awareness of an approaching threat, emergency preparedness, level of education on potential hazards, etc.) is a key factor in human vulnerability and notes that this information is usually poorly preserved in the aftermath of an event. This was true of Waitākere. While evacuations were undertaken by local and regional authorities some residents chose to stay. Of those who stayed, it is not known which houses were occupied at the time of the event, or the preparedness of residents or their level of education and understanding around the potential hazards. Had it not been for these evacuations, however, it is almost certain that many more people would have lost their lives. Consequently, as there were minimal casualties for an event of this scale, estimating the vulnerability (both human vulnerability and the conditional probability) for the many atypical cases becomes difficult as there are few examples to compare to, which results in the application of judgement and inherent uncertainty.

Observations of building damage from Waitākere generally agree with Kang & Kim (2015) that as debris heights approach 1 m, the possibility that a dwelling will collapse is very high. However, many atypical examples of inundation that contradict this observation were observed, including instances of about 5 m of debris flow height resulting in minimal building damage, buildings "rafting" downslope with debris, and bottom floors of buildings being destroyed but upper floors remaining intact. Additionally, human vulnerability can vary spatially when considering internal building inundation scenarios. Furthermore, quantifying the impact that entrained vegetation has on landslide debris volume and structural vulnerability (and therefore vulnerability) is difficult, given the inherent variability in cover, type and outcome.

5.2 UNCERTAINTY IN EVALUATING VULNERABILITY

A key conclusion from the review of published literature and observations from the Waitākere landslide events is that there is a significant amount of uncertainty in predicting the outcome as it relates to human vulnerability to a given landslide. This is primarily due to the range of available outcomes for any single event, outcomes which rely heavily on many contributing factors, and/or factors that are difficult to quantify. For example, it is difficult to predict if a building experiencing "total" inundation will be picked up and "rafted" downslope, or if the building is completely destroyed, and if this impact on the building will result in a person's death. The same is true for most hazards presented by landslides (e.g. internal building inundation, undermining of buildings, impacting rockfalls, etc.). There is a degree of 'randomness' generated by catastrophic events, which results in uncertainties that are difficult to quantify. This randomness and uncertainty often requires practitioners to adopt a precautionary approach, often resulting in the assessment of a worst-case scenario, which assumes the person is in the wrong place at the wrong time. This essentially eliminates human behaviour which, as highlighted by Pollock & Wartman (2020), is a key factor in human vulnerability.

The main method for evaluating both human vulnerability and adopting a specific conditional probability value for vulnerability is having proxies on which to draw upon, however, this is made difficult by limited published information. Estimating human vulnerability for larger scale events is in many respects easier because the damage scenarios can be more certain, given can be more site-specific data to draw from. However, for smaller scale events evaluating vulnerability can be difficult due to variability in building construction and limited proxies. Furthermore, given that human vulnerability is often a function of structural vulnerability, and geotechnical practitioners are not structural engineers, probability estimates rely on a significant amount of professional judgement and experience. Thus, for smaller scale landslide events, uncertainty in the vulnerability value is likely to be much greater and consistency between practitioners is likely to be variable.

Uncertainties related to the element at risk also impact the assessment of vulnerability. Generally, the element at risk is considered to be the occupant with the highest exposure to the hazard (i.e. the person with the highest temporal probability). The two people who tragically lost their lives during the event were inside a dwelling in Muriwai after it was inundated by a debris flow. The dwelling subsequently collapsed killing both inside. However, these two people were not regular occupants of that dwelling, rather they were volunteer firefighters who had intervened to remove the occupants from this dwelling, after an initial debris flow impacted the dwelling but didn't completely destroy it. In other words, they were people with a low temporal probability.

6 CONCLUSION

- The term vulnerability needs to be understood in terms of the context that it is being used. As discussed, it can relate to a specific conditional probability used in the calculation of loss of life or as an overall human susceptibility to landslide hazards.
- Conditional probability values of vulnerability presented in AGS (2007) have limited scenarios and broad ranges in the data.

- Additional recommendations based on observations from the Waitakere landslide event have been included to provide a broader range of possibilities associated with similar events.
- The concept of overall human vulnerability must take into account consideration of human behaviour aspects impacting spatial and temporal probabilities.
- The performance of various types of buildings against various types of inundation scenarios is well documented in published literature. However, there is much variability in the published results likely due to nuances in building design. As such, proxies using published information should be selected carefully.
- Structural vulnerability as a result of undermining of buildings and rockfall is not well documented in published literature.
- For many landslide hazards, human behaviour is the leading factor in determining human vulnerability. Evacuations in Waitākere likely saved many lives. However, behavioural information is often poorly preserved in the aftermath of a catastrophic event. Additionally, human behaviour can include intangibles that are difficult to measure, such as an individual's level of education, preparedness, and awareness of an approaching hazard.
- Estimating both overall and specific aspects of vulnerability is an uncertain process given the many different contributing factors and given the lack of available behavioural information, which inform all the possible outcomes. This uncertainty in outcome generally forces practitioners to adopt a conservative, worst-case scenario approach, assuming a person is in the wrong place at the wrong time, which removes the behavioural aspect entirely.

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