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Understanding and quantifying the impact of earthquake-triggered landslides in the Wellington area

E. Kianirad, A. O'Donnell, W. Yang, T. Lai & M. Mahdyiar
AIR Worldwide Inc., Massachusetts, USA.

ABSTRACT

In addition to ground shaking, earthquakes can generate secondary hazards such as fire following earthquakes, tsunamis, liquefaction, and landslides. In many previous earthquakes, these sub-perils were major causes of devastating losses to life, property, and infrastructure, demonstrating the significance of earthquake sub-perils.

The Wellington region is prone to major earthquakes and numerous studies have identified and evaluated landslide hazard in this region. However, most of the studies were focused on hazard assessment or evaluating the risk of building damage qualitatively.

In this study we have explored and quantified the impact of earthquake-triggered landslides in terms of direct and indirect economic losses caused by damage to buildings, contents, and loss of use (downtime). Utilizing the recently updated AIR Worldwide Earthquake Model for New Zealand, a probabilistic multi-peril modelling approach is used to quantify the impact of earthquake-triggered landslides. The results of this study indicate that for low return periods the losses are limited to millions of dollars. However, for large but rare events, losses due to liquefaction and landslide can exceed billions of dollars, increasing the total loss caused by a large earthquake by about 25%. In such an extreme catastrophic scenario, the total loss could exceed 60 billion dollars with large social and economic impacts on the entire country of New Zealand.

Paper 332

1 INTRODUCTION

In addition to ground shaking, earthquakes can generate secondary hazards such as fire following earthquakes, tsunamis, liquefaction, and landslides. In many previous earthquakes, these sub-perils were major causes of devastating losses to life, property, and infrastructure. The fire after the 1906 San Francisco earthquake, the tsunami generated by the 2011 Tohoku earthquake in Japan, widespread liquefaction experienced during the 2010-2011 Canterbury Earthquake Sequence, and the tsunami and ground failure from the recent earthquake in Palu, Indonesia are a few examples demonstrating the significance of earthquake sub-perils.

The Wellington region is prone to large magnitude earthquakes and numerous studies have highlighted the danger and importance of earthquake-induced landslides in this area (e.g., Brabhaharan, et al., 1994, Hancox et al., 1997). However, most of the studies focused on qualitative assessments of the hazard or the risk of building damage. One such was conducted for the Wellington Regional Council by Davey and Shephard (1995). This study investigated the impacts of two major earthquakes on buildings and the population in Wellington City and the immediate suburbs but did not include Porirua and Lower Hutt which were the subjects of other similar studies. The scenarios considered included; 1) a magnitude 7 earthquake located about 100 km away from the study area at a depth of 15 to 60 km, and 2) a magnitude 7.5 earthquake on the Wellington-Hutt Valley Segment of the Wellington Fault at 30 km depth. The impact of ground shaking, fire following earthquakes, liquefaction, and landslide was explicitly considered in the evaluation. For this study, damage to residential, commercial, and industrial buildings was estimated at 178 and 2,252 million NZD (in 1993-dollar values), respectively, for the two scenarios (Davey and Shephard, 1995).

As part of a study on tsunami-genic events, Cousins et al. (2009) evaluated the impact of four scenarios on a portfolio of buildings in the Wellington region. The earthquake loss modelling approach considered the impact of ground shaking, tsunami, liquefaction and landslide where the MMI was increased to account for damage from liquefaction and landslide. For a M_w7.5 earthquake on the Wellington Fault and a M_w8.2 on the Wairarapa Fault, the total building losses were estimated as $13.7 and $9.2 billion NZD, respectively. The tsunami had minor contribution into these two scenarios and contribution of landslide was not reported separately. A similar study was repeated by Cousins et al. (2014), for 8 earthquake scenarios. In the new study, the total building repair cost was estimated as $16.6 and $11.4 billion NZD for a M_w7.5 earthquake on Wellington Fault and M_w8.2 on the Wairarapa Fault, respectively.

Using the recently updated AIR Worldwide Earthquake Model for New Zealand, a multi-peril modelling approach is used to quantify the impact due to all earthquake perils (ground shaking, liquefaction, landslide, tsunami, and fire following) for historical and extreme disaster scenarios as well as a simulated catalogue of probabilistically sampled earthquakes. This study places particular emphasis on quantifying the impact of earthquake-triggered landslides in terms of direct and indirect economic losses caused by damage to buildings, contents, and loss of use (downtime). The geographical extent of this study focuses on the greater Wellington area which includes Wellington City and the surrounding urban centres including Miramar, Hutt Valley, and Porirua but not Otaki or Masterton.

2 EARTHQUAKE HAZARD IN WELLINGOTN

Due to its location at the plate boundary between the Australian Plate and Pacific Plate and right above the Hikurangi subduction zone, the Wellington region is exposed to very strong earthquake activity and seismic hazard. Large earthquakes typically occur along major faults. Based on observed seismicity over the past 180 years as well as through recent paleoseismological studies, several major active faults have been identified within the Wellington region as shown in Figure 1.

Figure 1: Active faults near Wellington City (after Langridge, 2016)

The Wellington Fault is a shallow strike-slip fault with a length of more than 70km and approximate slip rate of 6 mm/yr with a characteristic magnitude of about M_w7.5. Due to its proximity to a heavily urbanized area and its ability to produce relatively strong earthquakes, the Wellington Fault poses very high seismic risk to the Wellington area and has been well investigated (e.g., Rhoads et al., 2011; Robinson et al. 2005). The recurrence interval of events occurring on this fault is approximately 840 years (Stirling et al., 2012).

The other major fault in the region is the Wairarapa Fault, which ruptured in 1855 with an earthquake estimated at M_w8.2. This earthquake is by far the largest earthquake that has occurred in New Zealand in modern history. The Wairarapa Fault is a complex crustal fault with strike-slip and reverse faulting mechanisms that extends to the depth of about 35 km, with a fault length of more than 150km and a slip rate of about 9 mm/year (Stirling et al., 2012). The recurrence interval of this fault is approximately 1200 years, and the expected magnitude of M_w8.2 (Stirling et al., 2012).

3 LANDSLIDE HAZARD IN WELLINGTON

Rainfall-induced landslides occur relatively frequently in the Wellington region. One recent example includes the landslides which occurred during heavy rain in July and August of 2008. In the New Zealand National Landslide Database developed and maintained by GNS Science (Rosser et al., 2017), 1785 landslides have been mapped in the Wellington Region. Only 135 of these landslides were triggered by earthquake, 520 were triggered by rainfall, and the triggering mechanism is unknown for the rest. From the 135 landslides which were triggered by an earthquake, 9 landslides are associated with 1904 Cape Turnagain Earthquake, 2 with 1934 Pahiatua earthquake, 17 with the June 1942 Wairarapa Earthquake, and 1 with the August 1942 Wairarapa Earthquake. The remaining earthquake-induced landslides have not been associated with any particular event.

The 1855 Wairarapa Earthquake (estimated M_w 8.2) caused widespread landslides across the Wellington region. Hancox (2005) summarized previous studies related to the effects of landslides and liquefaction caused by the 1855 earthquake and highlighted the hazard posed to the region by these perils if a similar earthquake were to strike the region again today.

Most earthquake-triggered landslides that were associated with historical events have occurred in areas that are scarcely populated. If those exact same landslides were to occur today, they may cause damage to agricultural lands and roads but not necessarily damage to the general population. However, we know from observations in the 2016 Kaikoura earthquake and experiences worldwide that a major earthquake can cause widespread landslides, which can be devastating if they occur in a major population area.

In the 1990s, several studies to assess the seismic hazards in the Wellington region were conducted focusing on urban areas and main highways in the region. As part of that effort, slope failure hazard in the area was studied using the methodology described by Brabhaharan (2000). The result was published as a map delineating slope failure susceptibility in the area (Brabhaharan et al., 1994). Since its development and publication, the map has been used in hazard mitigation planning and emergency management.

4 METHODOLOGY

AIR-Worldwide (AIR) has developed earthquake loss estimation models for many countries around the globe. These probabilistic earthquake models capture complex seismicity and regional differences in ground shaking attenuation through a stochastic event simulation approach. Monetary losses, casualties, and loss of use (downtime) are estimated based on the vulnerability of the buildings and contents where the vulnerability is determined by characteristics of the buildings and contents exposed to the hazard. These models provide a basis for making informed decisions in managing seismic risk for the insurance and reinsurance market as well as financial (i.e., insurance linked securities), corporate (enterprise risk), and government entities looking to quantify and manage their risk.

The newly updated AIR Earthquake Model for New Zealand explicitly models damage due to ground shaking, landslide, liquefaction, tsunami, and fire following earthquakes. The model itself contains numerous components including seismicity, ground shaking attenuation, ground deformation, tsunami inundation, conflagration, and vulnerability modules. Each individual component has undergone extensive calibration and validation using claims data, post-earthquake damage data, and published research. Locally developed published and unpublished research and datasets that have been obtained through collaboration with local experts were extensively used in the development of the model. This includes comparing the modelled monetary losses against public and private insurance claims and reported industry loss estimates for residential, commercial, and industrial assets.

In order to perform these analyses on a country-wide basis, AIR has developed and maintained a detailed database containing the inventory of all properties at risk in New Zealand. This database (known as the Industry Exposure or IE) contains the important characteristics of each asset including the location, structure type, construction material, occupancy, height, and replacement value. The sources used for developing this proprietary database include various government organizations and private vendors. Figure 2A shows the relative distribution of building replacement value contained within the Industry Exposure in the Wellington area.

In the AIR Earthquake Model for New Zealand, earthquake-triggered landslide is simulated explicitly for the entire country. The landslide module relies on local geological and geomorphological maps to identify material strength and terrain slopes to define different levels of landslide susceptibility. Modelled ground shaking intensity and seasonal changes in slope wetness are then coupled with landslide susceptibility to estimate the landslide hazard which is used to calculate damage and loss. Figure 2B, 2C, and 2D show the ground slope in degrees that have been derived from DEM, surficial geology, and landslide susceptibility for dry soil conditions, respectively in the Wellington region.

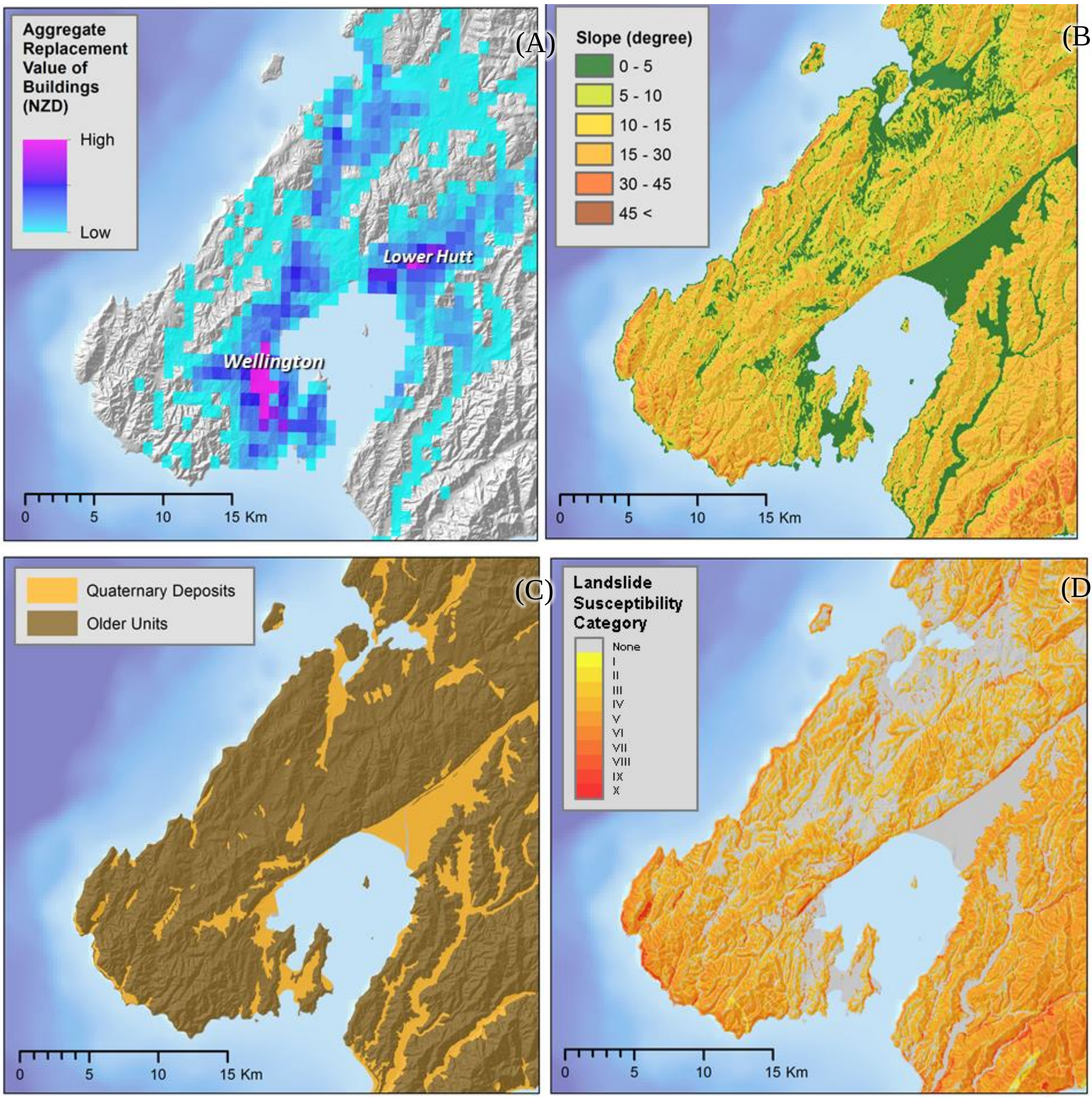

Figure 2: A) Distribution of building replacement values, B) ground slope, C) surficial geology (based on GNS QMAP, Begg & Johnston, 2000), and D) Landslide susceptibility in the Wellington area.

Precipitation data is used as an index to determine the wetness of slopes and saturation of soil which impact the likelihood of ground failure during an earthquake where more heavily saturated soils are more likely to result in landslides. In Wellington City, the median monthly precipitation varies between 55 and 132 mm based on data from NIWA (National Institute of Water and Atmospheric Research) with February being the driest and June as the wettest month.

The landslide module is a physics-based model which relies upon the mechanics of slope failure and employs models of seismic slope stability to assess the deformation of the slope and probability of slope failure during an earthquake. The damage caused to buildings by earthquake-induced landslides is estimated as a function of permanent ground displacement and probability of slope failure

The overall performance of the model for predicting landslides was validated against observations from historical earthquakes including the 1987 Edgecumbe, 2003 Fiordland, 2010-2011 Canterbury Earthquake Sequence, 2013 Seddon, 2013 Lake Grassmere, and 2016 Kaikoura earthquakes.

5 DAMAGE DUE TO EARTHQUAKE-INDUCED LANDSLIDE

5.1 Historical Recurrence Scenarios

Earthquake shaking has been felt in the Wellington Region frequently, but the 1855 M_w8.2 Wairarapa Earthquake is believed to be the most severe earthquake to have impacted the Wellington region and even New Zealand in the last 180 years. Based on historical reports, the earthquake triggered extensive slope failures in the region as far away as some northern areas on the South Island (Hancox et al., 1997). Based on historical data less than 5,000 people were living in Wellington at that time (Bloomfield, 1984) while in 2017, the total population of the Wellington region was estimated at 514,000 with only 213,000 people living in Wellington City.

Wellington and the surrounding area have expanded significantly. The landscape contains many buildings perched on the side of very hilly slopes as an indication of such a growth. Using AIR's Earthquake model for New Zealand, it is estimated that the 1855 Wairarapa earthquake would cause about $60 billion NZD in ground up loss if it were to occur with today's building inventory. In such a scenario the landslide contribution to the total loss is estimated around $5 billion NZD. This number includes more than $900 million NZD damage to residential land in addition to the damage to physical property. The cost of restoring the slopes and retaining structures to a condition which is suitable for repair or re-development is considerable.

Model results for other historical earthquakes indicate that no other recent earthquake (including the 1904 Cape Turnagain, 1934 Pahiatua, June and August 1942 Wairarapa, and 2016 Kaiakoura earthquake) would cause any significant landslide loss. The estimated landslide loss for repeat of these events is negligible or relatively minor (several million dollars NZD) compared to the expected damage caused by ground shaking. The model results are in good agreement with historical observations with respect to observed landslide damage.

5.2 Probabilistic Scenarios

The financial impact of earthquake-triggered landslides was also evaluated using a stochastic catalogue of simulated earthquakes. Using this type of catalogue, it is possible to determine the expected return period for certain levels of monetary loss where this catalogue includes all possible sources of earthquakes that could impact the Wellington region including the Wellington and Wairarapa Faults as well as the Hikurangi subduction zone.

From these analyses it has been determined that the losses due to earthquake-triggered landslides is small (on order of a few to ten of million dollars NZD) for short return periods (approximately 50 to 100 years). However, for return periods exceeding 500 years, the landslide losses in the Wellington exceed $1 billion NZD. It should be understood that using this probabilistic approach, the return periods represent the frequency of expected loss and not necessarily the return period of earthquakes from a hazard perspective. These model results are consistent with the historically observed levels of landslides damage and losses in the Wellington region in the last 150 years.

5.3 Extreme Catastrophic Scenarios

For an extreme catastrophic perspective, the impact of two scenarios are examined: 1) a M_w 7.5 earthquake on the Wellington Fault, and 2) a M_w 8.2 earthquake on the Wairarapa Fault. Scenario 1 is intended to represent a more realistic event and while Scenario 2 is less likely, it is a scientifically plausible scenario for this region.

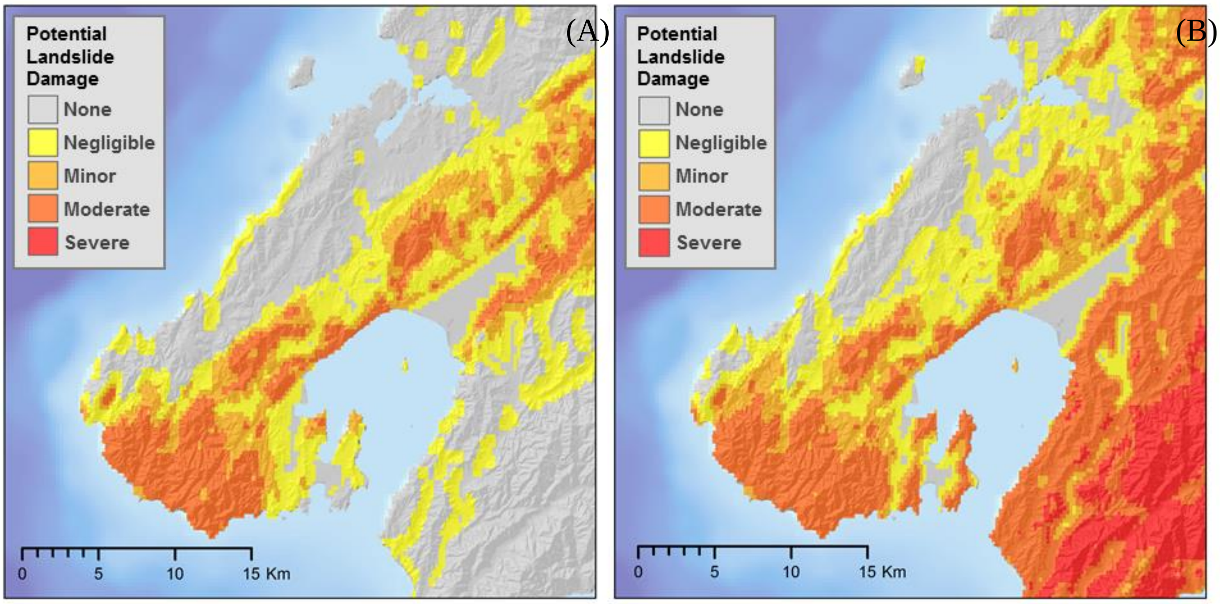

Figure 3: Modelled landslide damage, assuming uniform 1-story building across the region for; A) a M_w7.5 Earthquake on the Wellington Fault, and B) a M_w8.2 earthquake on the Wairarapa Fault.

The level of ground shaking for either scenario will be very violent, and buildings close to rupture will experience ground shaking that will likely exceed the ground acceleration for which they were designed. In such a scenario, moderate to severe damage is expected in most of the region largely due to strong shaking. Liquefaction has the potential to cause significant damage to artificial fill (reclaimed lands) of Wellington City and port facilities, Petone, and Lower Hutt. Landslide can also cause significant damage to suburban areas and particularly to residential housing built into the hillsides. Figure 3 shows the potential landslide damage from both scenarios for a 1-story residential home throughout Wellington and the surrounding area.

For Scenario 1 the total loss is expected to exceed $40 billion NZD while the losses for Scenario 2 have the potential to exceed $60 billion NZD. For Scenario 1, approximately 97% of the loss is estimated to occur in the Wellington area while for Scenario 2, the estimate is about 84%. Losses due to liquefaction and landslide can exceeds billions of dollars, increasing the total loss by more than 25%. Sub-peril contributions to total loss and impact on different sectors are summarized is Figure 4 for Scenario 2.

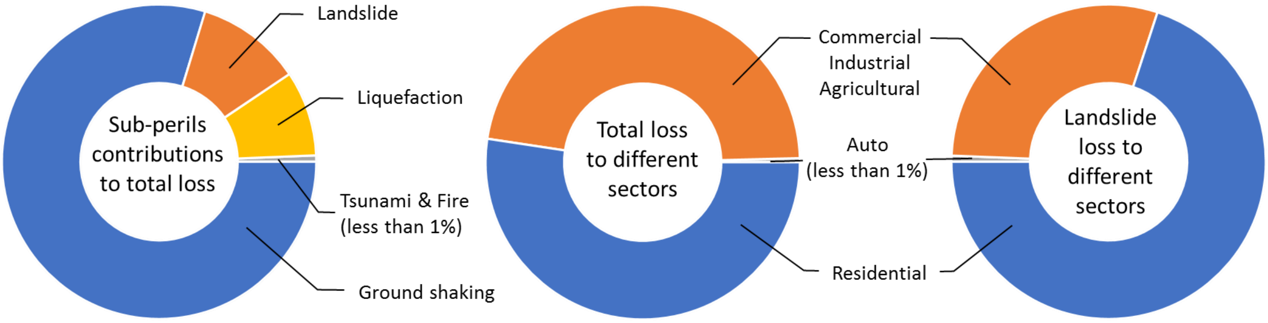

Figure 4: Contribution of sub-perils and losses to different sectors due to a M_w8.2 earthquake on the Wairarapa Fault in the Wellington Area.

The landslide and liquefaction perils are unique in that they have potential to cause damage to land. Even in the event that a building is completely damaged by ground shaking, the rebuilding on undamaged land is an option for recovery. However, in the case of landslide, slope failure could potentially make rebuilding on the land more expensive or completely unusable for future development. Such a situation imposed additional challenge to home owners, local authorities, government and the insurance industry as a result of the significant impacts of liquefaction and landslide/rockfall in the Port Hills area after 2010-2011 CES. One factor which will have significant impact on the monetary loss is the fact that any repair to retaining walls or foundations damaged due to ground failure, need to be based on the most up-to date building codes and best practice. Meeting the latest requirements for stability and load combinations in highly-seismic and mountainous areas like Wellington will increase the cost of repair and rebuilding considerably. In Scenario 2, our evaluation suggests that land damage due to earthquake-induced landslides can exceed $1 billion NZD.

6 CONCLUSION

In this study we have explored and quantified the impact of earthquake-triggered landslides in terms of direct and indirect economic losses caused by damage to buildings, contents, and loss of use (downtime) in the Wellington area. Utilizing the recently updated AIR Worldwide Earthquake Model for New Zealand, a probabilistic multi-peril modelling approach is used to evaluate the landslide hazard for multiple scenarios including; 1) historical recurrence scenarios, 2) probabilistic scenarios, and 3) extreme catastrophic scenarios.

This study demonstrates that for short return periods of 50 to 100 years, the landslide damage is small relative to damage due to ground shaking. However, for return periods exceeding 500 years, the landslide losses can exceed $1 billion NZD. For extreme catastrophic event scenarios, the landslide could cause multiple billions of dollars in loss where damage to residential land alone can exceed $1 billion NZD. The damage to utilities (water, electricity, communication) and infrastructure would also add to the material loss as well as exacerbate losses from downtime.

In summary, widespread and damaging landslides are expected to occur if a major earthquake were to strike the Wellington area. The slope failure and ground deformation due to landslide could damage buildings, block roads, interrupt utilities, and also damage residential land on the hillsides to a degree which it may be unsuitable or very expensive for repair or future rebuilding afterward.

In the hilly areas, there are many houses located close to the top or bottom of unsupported cuts into the hillside that do not have proper foundations or retaining structures. Many slopes were modified to construct roads without proper retaining structures that could withstand the dynamic forces during a major earthquake. These houses and roads are at high risk of damage due to landslide in a future earthquake event. Additional work by local and national organizations to survey the slopes and obtain more detailed site-specific information would be beneficial if they are translated into action plans that address these existing hazards.

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