

# PROBABLE LOSS ESTIMATION OF INFRASTRUCTURE DAMAGE DUE TO LANDSLIDE HAZARD: AN EXAMPLE OF GEOTECHNICAL RISK ASSESSMENT

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## ABSTRACT

With the rising cost of impact from natural hazards on public horizontal infrastructure (e.g. water supply networks), better management of natural hazards is required. The main options for managing the impacts from such events are risk acceptance, avoidance, mitigation and transfer (i.e. through insurance). Each of these options have a monetary cost. An optimal approach generally comprises a combination of options, which vary between asset types, locations and infrastructure owner requirements. To understand the costs and effectiveness of the risk management options, risk assessments are conducted to assess the likely damage and the associated reinstatement cost. This paper summarizes a case study that applied a model developed to assess the impact to council assets from seismic and co-seismic events (e.g. liquefaction and landslide) in order to estimate the probable loss. This paper focuses on the landslide hazard and risk analysis component. Using mapped historic landslides, the susceptibility of the geology and slope profile for future landslides can be quantified. This produced a landslide hazard factor which was grouped into a qualitative hazard descriptor. The output for the landslide hazard analysis was geospatially referenced to attribute assets to the modelled landslide risk. Through stochastic risk modelling, the total asset portfolio loss was modelled.

*Keywords:* Natural hazards, landslide hazard, asset management, risk assessment, landslide, insurance, geospatial modelling, stochastic modelling, loss modelling

## 1 INTRODUCTION

The 2010-2011 Canterbury Earthquake Sequence (CES) highlighted the severe and far-reaching effects of essential infrastructure loss. This was highlighted again during the 2016 Kaikoura earthquake with the impact to the national transportation network. These earthquakes have demonstrated the vulnerability of infrastructural assets to natural hazards. Due to the effects of these earthquakes, as well as meteorological events resulting in flooding and severe storm phenomena, local and central government agencies are considering their own network risks and exploring ways to improve their resilience.

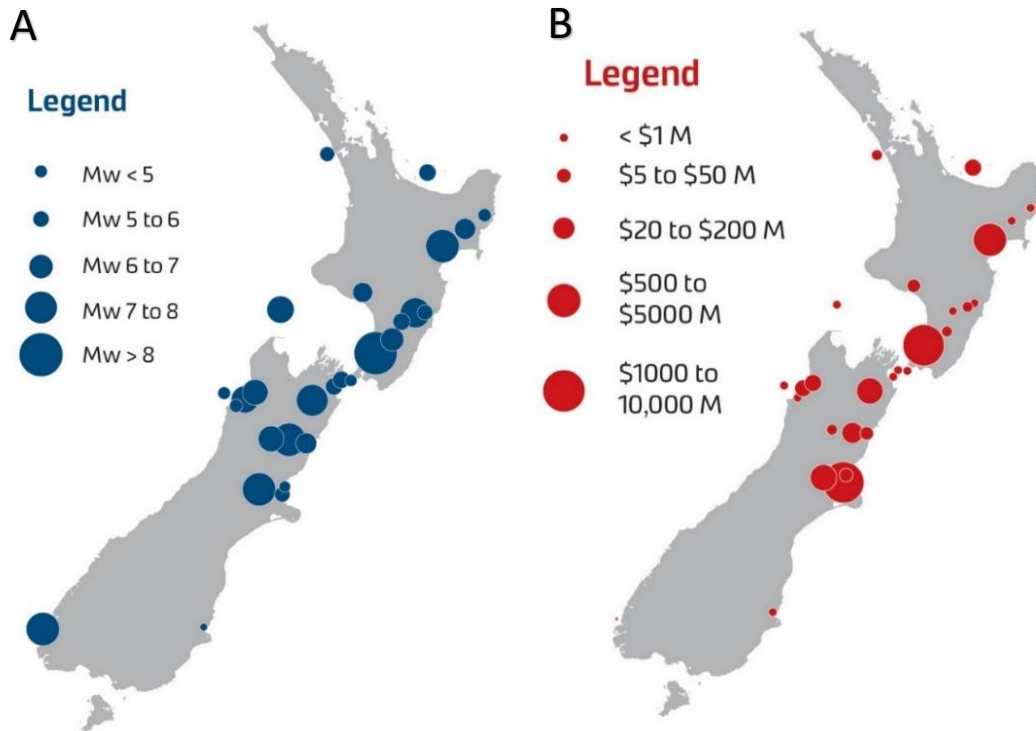
Risk mitigation and resilience enhancements of infrastructure requires a multi-faceted approach, drawing on an understanding of natural hazards and asset vulnerabilities, potential policy interventions, as well as improvements to readiness and response capabilities. A key part of this process requires modelling of potential losses and the mitigation of those losses using risk transfer tools.

This paper discusses the vulnerability assessment applied to three-waters (water supply, wastewater and stormwater) networks exposed to seismic and co-seismic (liquefaction and landslide) hazards. The landslide hazard analysis is expanded on with a detailed methodology. It also discusses work that has been done by Tonkin + Taylor (T+T), in partnership with Aon New Zealand, to estimate the financial loss to three waters networks from earthquakes. Historic precedence and modelling both demonstrate that seismic induced landslides can have a significant impact on lifeline infrastructure and communities. The Queenstown Lakes District Council (QLDC) area is presented as a case-study of the landslide hazard analysis.

## 2 BACKGROUND

New Zealand is a seismically active country. This is due to New Zealand being situated on the convergent Australian and Pacific tectonic plate boundary. In the South Island, the Alpine Fault characterises the land expression of this plate boundary, before extending north-east off shore of the North Island as the Hikurangi Subduction interface.

New Zealand has experienced several significant earthquakes since European settlement. Figure 1a shows the spatial distribution of some of the known significant earthquakes from the 1840s through to present day.



**Figure 1: A) Spatial distribution of significant earthquakes from the 1840s to present day that would impact main New Zealand centres if the event occurred today (Geonet, 2016). B) Estimate of the damage potential (in dollars) to current three waters infrastructure if these historical earthquakes were to occur today. Note: The data presented represents a qualitative engineering assessment and is not directly derived from model results.**

The 1929 Mw 7.1 Arthurs Pass earthquake resulted in multiple seismically-induced landslides, which blocked roads and damaged railways connecting Canterbury to the West Coast and resulted in transportation outages for several months (McSaveney, 1982). Fortunately, the epicentre was in a sparsely populated area. However, a few months later the Mw 7.3 Murchison earthquake struck 65 km north of Murchison, producing landsliding within the town, causing 17 fatalities, extensive building and bridge damage and outages to lifeline infrastructure (Dowrick, 1994; Benn, 2005).

The 1968 Mw 7.1 Inangahua earthquake on the west coast of the South Island also produced extensive landsliding that caused substantial roading damage from either debris or road collapse. Additionally, bridges collapsed, water supply pipes were damaged beyond repair, and power and phone network outages occurred (Douglas, 1968; Callan, 2010).

The 2010-2011 CES illustrated the severe impacts that earthquakes can cause to densely populated centres. The Mw 6.3 2010 earthquake had an epicentre very close to Christchurch and resulted in severe widespread liquefaction across the city. This severely damaged both the above ground buildings and infrastructure, as well as the buried infrastructure such as the three-waters network (Cubrinovski et al, 2014). Rockfall and landslides impacted areas of Christchurch as well. This was predominantly focused around the Port Hills, Sumner and Redcliffs to the south of the CBD, causing damage to buildings, structures and roads.

The most recent significant earthquake to impact New Zealand was the 2016 Kaikoura earthquake, which was a larger event at Mw 7.8. This event had an epicentre that was not near densely populated centres, therefore it resulted in minimal three-waters infrastructure damage (Hughes et al, 2017). However, seismically induced landslides and rockfalls caused significant road and rail damage and extensive periods of outage followed by reduced capacity of these transport networks. At the time of writing this paper the restoration of these networks is ongoing and reduced capacity continues. This had (and continues to have) substantial secondary impacts for the transport and logistics sector, as the main route south from the top of the South Island to Christchurch was closed for over a year (Robinson, 2018). Subsequently the local economy was impacted as tourism, a significant sector for Kaikoura, was affected with access reduced and repairs to accommodation and tourism structures still taking place.

Apart from earthquake magnitude, the financial loss is also sensitive to the surrounding population and infrastructure concentration. For example, the Mw 7.8 2008 Fiordland earthquake was a large earthquake, but resulted in no damage and loss due to its location and limited assets in the region. By comparison, the Mw 6.3 event on 22 February 2011, is relatively small, however the close proximity of the earthquake epicentre to Christchurch City and the high potential for

liquefaction in some of the soils underlying the city meant that it caused extensive damage to three waters infrastructure, resulting in significant financial losses.

Even with a relatively short earthquake history, it is evident that a greater understanding of the estimated damage, outage and financial loss is needed to plan how to mitigate risks to assets. Given the increase in urban development and the installation of vast infrastructure networks, it is likely that if some of the New Zealand historic earthquakes had occurred in modern times, there would have been greater asset damage and subsequent financial loss. Figure 1b shows an estimate of the financial loss to three-waters infrastructure if the earthquakes shown in Figure 1a were to occur in the present day.

Apart from historic events, predictive modelling can also be used to highlight the vulnerability of infrastructure to damage in future events. This can be applied to estimate damage, outage and economic loss from future events with significant co-seismic landsliding. Robinson et al. (2015) modelled the estimated damage and infrastructure (transport, power and three-waters) outage from an Alpine Fault earthquake with co-seismic landsliding across the South Island. This highlighted significant landsliding would isolate the West Coast and impact access, either extended travel times or restrict routers, across the Southern Alps for over a year.

Work undertaken for Queenstown Lakes District Council (QLDC) has been used as the case study for this paper. Queenstown is situated approximately 80 km east of the Alpine Fault. The region's main centres are situated among the glacial-carved Southern Alps mountain range. Several other faults are within the region that could impact the district, such as the Cardrona-Fault-Zone and Moonlight Fault. These geological conditions create a significant risk to the Queenstown region, with glacial and alluvial sediments on the flats creating land that is susceptible to liquefaction, as well as the mountains creating landslide susceptible conditions (Turnbull, 2000). With these potential hazards, assets within the region are vulnerable to damage and financial losses.

### 3 PROBABLE MAXIMUM LOSS FRAMEWORK

The following four step process has been developed to determine an estimate of the Probable Maximum Loss (PML):

- Step 1: Compiling asset data
- Step 2: Defining the hazard
- Step 3: Estimating the damage
- Step 4: Determining the financial loss

Each of these steps will be discussed below and discussed with relation to three waters pipes as an example of the methodology.

#### *Step 1: Compiling asset data*

A critical component when determining expected damage and loss from any event is understanding the assets being assessed. An asset inventory was compiled containing specific attributes for each asset, their location and valuation. For this assessment QLDC provided their three-waters asset database and the valuation schedule.

Asset attributes are also key in determining the asset's potential for damage, commonly referred to as vulnerability characteristics. As an example, for pipe network assets the attributes considered are:

- Construction materials
- Pipe diameter
- Age of the pipes and relationship to asset design life
- Service type and mode of function e.g. are they pressurised or gravity systems
- Value of the pipes

A crucial piece of information is the asset location. As a result, typically this data needs to be provided in a geospatial format, as it allows for spatial association with the hazard model (discussed in Step 2). This is typically provided in either an ArcGIS geodatabase or shapefiles which allows the assessment to be conducted using Geographic Information System (GIS) software.

#### *Step 2: Defining the hazard*

Another key component is understanding the regional natural hazards. As part of this step, data was collated from a range of sources including; published material (e.g. Benn et al, 2005), consultancy and council reports (e.g. Opus, 2005), New Zealand standard guidelines, previous work Tonkin + Taylor has conducted, expert knowledge of the region, and publicly accessible data sources (e.g., New Zealand Geotechnical Database).

For the purpose of the assessment undertaken for QLDC, geospatial layers were created for the seismic extent with associated intensity, which for the purposes of this assessment a PML study is defined as a 1000 year ARI event, along

with layers for the respective considered co-seismic hazards (e.g. liquefaction and landsliding). These were developed using a combination of published relevant methodologies and expert judgement where applicable. Refer to the methodology section for a detailed description of how the landslide susceptibility layer was produced (section 4).

### ***Step 3: Estimating the damage***

Damage was estimated utilising the information collected in Steps 1 and 2 above. Using GIS tools, the hazard data is overlaid onto the asset data to attribute a hazard intensity for each asset. Vulnerability functions from published information were used to estimate damage for given hazard intensities. For example, for pipe infrastructure, Cousins (2013) methodology for assessing pipes damage from seismic and co-seismic hazards was used. This applies both the hazard characteristics from shaking, liquefaction and landslide susceptibility, as well as pipe diameter, age and material type to estimate pipe break rate per kilometre (Cousins 2013). Liquefaction and landsliding can cause breakages and differential displacement (both vertical and horizontal) of pipes. Specific pipe characteristics can alter the number of breaks, for example brittle pipes are more likely to break compared to ductile, which can tolerate more deformation without rupturing, therefore they can remain operational with greater deformation.

### ***Step 4: Determining the financial loss***

The final step was to determine the financial loss for the network. This used the output of Step 3, where each asset was attributed a damage ratio. One of the key assumptions required in this step was the determination of whether the asset would be completely damaged and need to be replaced, or if it would be economically viable to repair the pipe. Stochastic sampling is carried out from a distribution of the asset damage ratio with associated variance to calculate the ratio of repair versus full replacement that would be needed, in order to subsequently calculate the financial loss. This approach allowed loss value ranges to be produced, and therefore better representation of the uncertainty in the process. The total financial loss was then summed to determine an estimate of the PML, which for this assessment is based on a 1000 ARI event.

## **4 METHODOLOGY AND RESULTS**

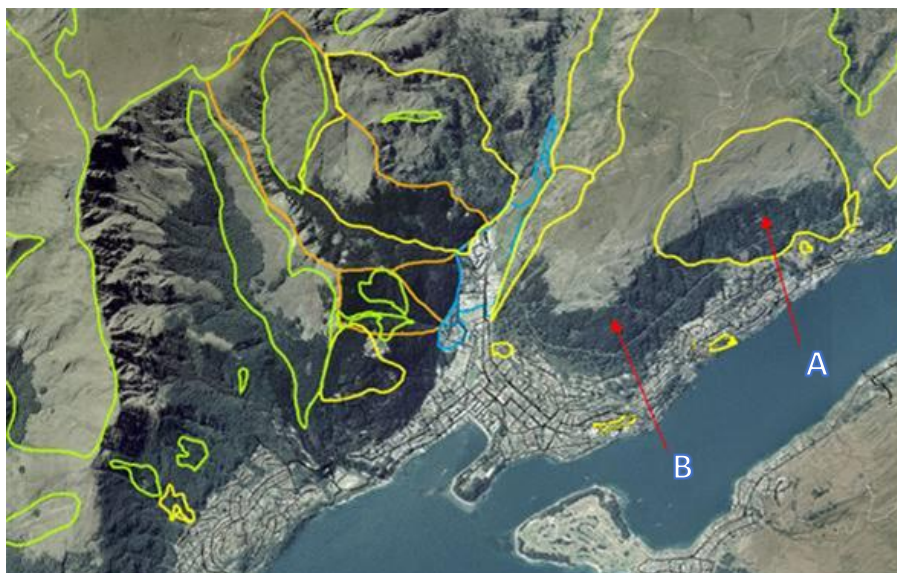
As part of the assessment for QLDC, seismic hazard, liquefaction and landsliding were modelled. For the purpose of this paper, only the landslide hazard methodology is discussed. To assess the areas that are potentially vulnerable to seismic-induced landslides, a literature review was undertaken, along with a desktop-based review of the QLDC geospatial historic landslide layer (Available on the QLDC GIS viewer). Previous reports and published material (Opus, 2005) highlight that given the QLDC regions high seismic hazard and steep topography, an understanding of the landslide hazard is of high priority.

A geospatial process to differentiate landslide susceptibility areas was applied. For the purposes of this assessment, only landslide evacuation areas (i.e., the landslide source material) was modelled. This is because for buried infrastructure, landslide evacuation is the most likely cause of damage. A landslide susceptibility geospatial layer was developed to correlate with asset locations. To develop the landslide susceptibility layer, an array of data from a variety of sources was used. For the QLDC region, Hancox et al. (2002) derived general associations between the occurrence of earthquake-induced landsliding and slope angle and geology. The presence or absence of existing landslides in an area does not appear to have been a factor in determining the distribution of the susceptibility zones in output maps. This is because susceptible geology may not have moved yet, but may still move in future events. This is acknowledged in the applied methodologies.

The QLDC historic landslide layer is a geospatial inventory of known landslides mapped using aerial photographs or field mapping. The landslide inventory layer is likely to include historic landslides triggered by both rain and seismic events. However, no date or landslide triggering mechanism is held within the attributes of the landslide inventory. A further limitation of the landslide inventory is that it only represents known historic landslides, therefore, it is not a complete representation of the landslide hazard from rain or earthquake events. Figure 2 shows an example of the QLDC landslide layer showing landslides and alluvial fans extent in Queenstown, filtered to the landslide evacuation extent, and not showing the landslide debris extent. In Figure 2, A is pointing to a large schist landslide and B is pointing to an adjacent area of schist that has a similar slope angle, but does not appear to have been affected by large-scale landsliding. For our assessment such areas should be considered equally susceptible to future movement.

When assessing the susceptibility of an area to landsliding, a key consideration is the occurrence (or otherwise) of historic landsliding in this, or similar, terrain. In particular, physical parameters most closely associated with previous landsliding can be assumed to be controlling factors in the occurrence of any future landsliding – the past is the key to understanding the future (Flentje et al, 2007). This is where a detailed assessment of the landslide inventory becomes important in assessing susceptibility.

A normalised difference assessment was undertaken to identify areas of different landslide susceptibility, an approach that has been applied in major quantitative landslide risk assessments in the Whakatane, Ohope and Matata in the Bay of Plenty of New Zealand (Tonkin + Taylor 2013a; Tonkin + Taylor 2013b). This approach can identify and quantify combinations of factors, such as geology and slope angle, that are most closely associated with previous landsliding based on the landslide inventory. It is then possible to assign a numeric value to the relative density of landsliding for a given set of conditions. A zero-normalised difference means that an area has a proportion of the landslide inventory that is commensurate with its size, whereas areas with positive or negative values have greater and lesser occurrence of landslides respectively.



**Figure 2: QLDC landslide polygons identified and recorded geospatially overlaid on an aerial photograph. A) is pointing to a large schist landslide and the other arrow, B) is pointing to an adjacent area of schist that has a similar slope angle but does not appear to have been affected by large-scale landsliding. For our assessment such areas are considered to be equally susceptible to future movement.**

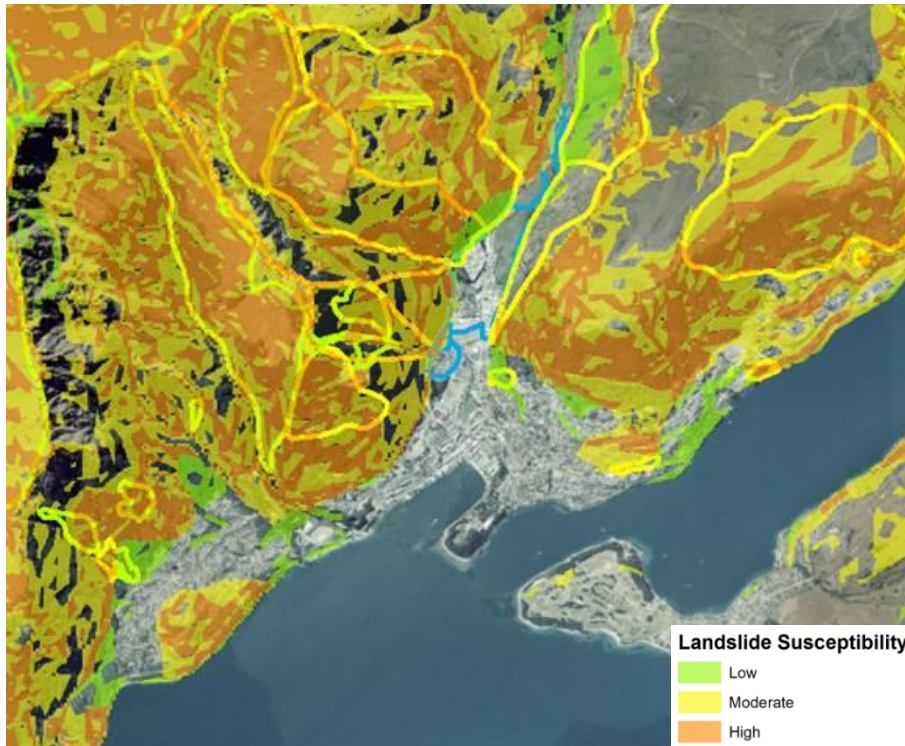
This normalised approach was applied to the Queenstown landslide layer dataset, using the 1:250k QMAP geology and 10° intervals (up to 60+°) slope classes developed from Land Information New Zealand (LINZ) national 25 m Digital Elevation Model (DEM). Through analysis of the locations of the existing landslides and the proportion of geology and slope that indicates landslide potential over the total area within the region was used to produce a relative susceptibility value. This relative susceptibility value to landsliding was subsequently applied to all other locations with the same combination of geology and slope angle.

Figure 3 shows the output of this normalised landslide susceptibility assessment. This indicates areas (including the area indicated in Figure 2) that are not currently mapped as having landslides, but may have future landslides based on the geological and topographic properties. A smoothing process was applied to the output in order to reduce the pixelation effect generated by the raw slope angle data. This was banded into classifications of low, moderate and high susceptibility. What this shows is that low-lying areas are not susceptible to landsliding due to the slow angle, but the higher slope angles are. The output was validated through manual review using engineering judgement, aerial imagery and historic aerial imagery by a senior engineering geologist.

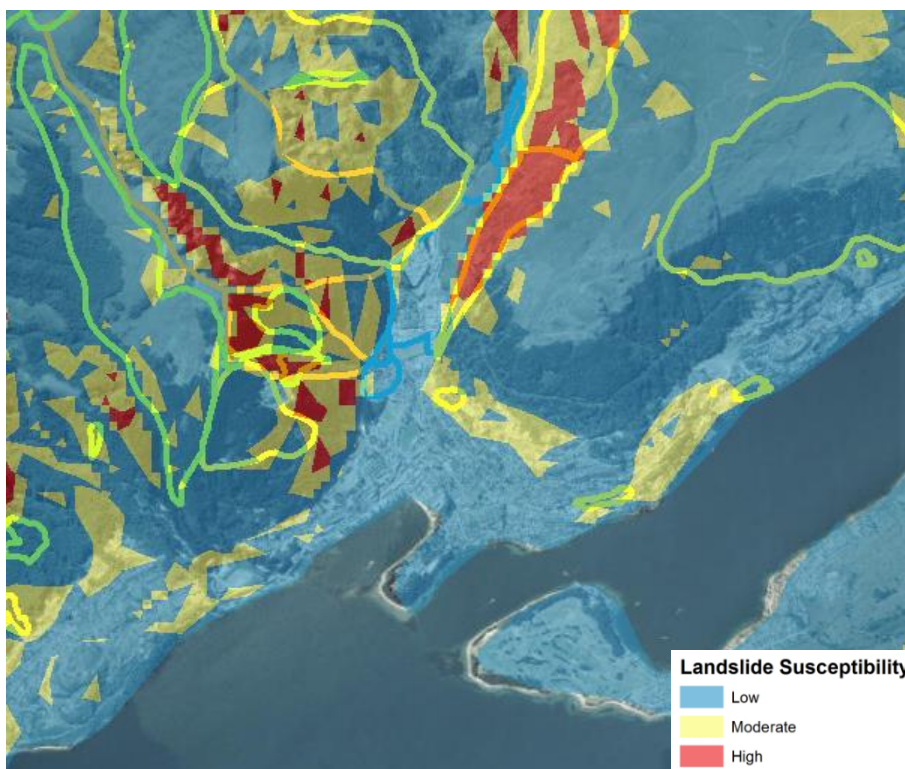
An alternate approach for modelling landslide susceptibility material method for the Central Otago region is presented in Opus (2005). This method is similar to that of the normalised difference approach (used in this paper), relating slope and geology to a susceptibility classification. To compare and cross check the normalised difference methodology with the approach described by Opus (2005), the 1:250k QMAP geology and 25 m DEM for slope gradient was used. The Opus (2005) approach is shown in Figure 4. This shows large areas mapped as low susceptibility, including known large existing landslides. It is worth noting that the Opus (2005) methodology is specifically for seismic-induced landslides, whereas the T+T approach, which is based on the inventory of all landslides, assesses overall landslide susceptibility irrespective of the trigger mechanism.

Comparison between Figure 3 and Figure 4 shows that the normalised difference landslide susceptibility model is broadly consistent with the method adopted by Opus (2005) (i.e. a certain combination of geology and slope angle is given a higher or lower landslide susceptibility rating). However, the T+T approach directly uses the inventory of known landslides in the determination and is able to quantify the differences in landslide susceptibility.

The Opus (2005) approach shows some areas that are susceptible to landsliding that are not identified using the normalised difference approach applied here. These are glacial till deposits at moderate slope angles and schist material at steep angles. Similar to other models there is uncertainty associated with this assessment of landslide susceptibility.

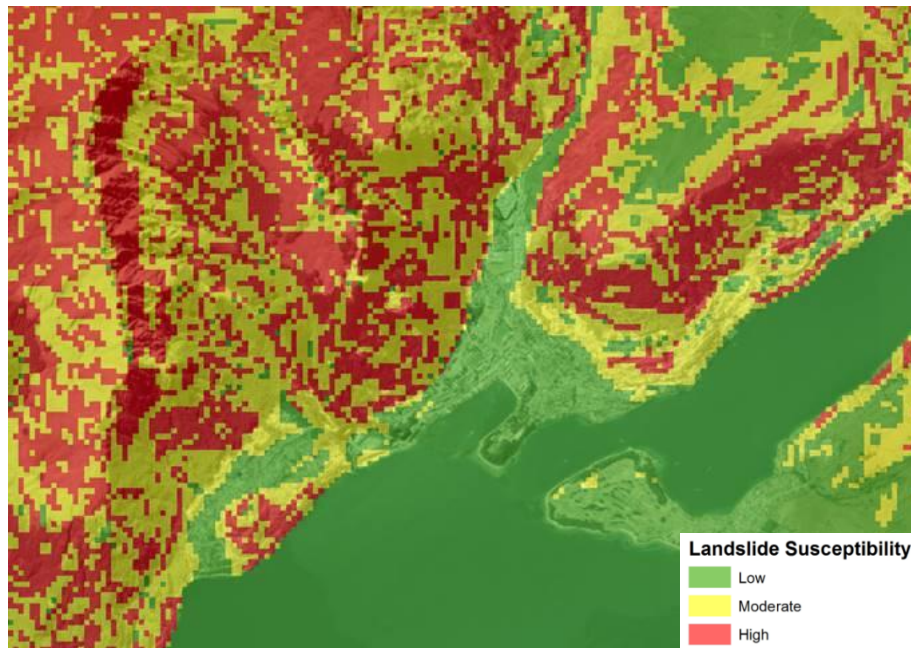


**Figure 3: Landslide susceptibility indicator using a normalised difference approach**



**Figure 4: The Opus 2005 seismic-induced mass movement logic applied to QMAP geology and NZ 25 m DEM slope base data with the QLDC landslide inventory layer**

For the purposes of loss estimation, it was considered appropriate to assess locations prone to instability by merging the outputs from the normalised difference and the Opus (2005) methodologies and take the maximum susceptibility classification for each grid cell. This methodology considers susceptibility of landslide evacuation area, which is appropriate for assessing pipe damage. The landslide susceptibility grid is classified into low, moderate and high seismic-induced landslide susceptibility (Figure 5). This highlights relevant areas of landslide susceptibility, sensitive to both the slope angle as well as geology. Relative susceptibility differences in geology is identified with differences in weathered versus non-weathered schists where the weathered is more susceptible to landslide at lower slope angles compared to the non-weathered within the district. This combination of the normalised difference and Opus (2005) methodologies ensured where one method identified susceptible areas and the other method had not, the areas were acknowledged as susceptible to future movement.



**Figure 5: Example of the seismic-induced landslide susceptibility area applied to the assets in Queenstown**

## 5 DISCUSSION AND CONCLUSION

The 2010-2011 CES highlighted the vulnerability of buried infrastructure networks to seismic and co-seismic hazards. It also highlighted the significance in maintaining services and how infrastructure outages can impact the affected communities. The 2016 Kaikoura earthquake, along with other New Zealand examples, display the landslide susceptibility of large areas, and the possible consequences to impacted population centres. Although the Kaikoura earthquake caused low direct damage due to the location of the epicentre, the event was of national significance impacting the main highway and rail line down the South Island and impacted tourism. At the time of submission, no main centre in New Zealand has been significantly impacted by co-seismic landsliding. However, the consequences for future large scale co-seismic landsliding (e.g. West Coast from Alpine Fault earthquake) have been modelled in previous research and can have not only high direct loss and damage, but subsequent significant impacts e.g. transportation outage. There are a number of centres at risk from co-seismic landsliding such as Wellington, Tauranga, Queenstown, Wanaka, and potentially other smaller settlements.

The landslide hazard assessment methodology requires a range of key pieces of data. An extensive landslide inventory was used, along with suitable resolution geological and topographic data, to establish susceptible areas. These information requirements highlight a potential limitation that might inhibit transfer of the methodology presented to different regions.

There are multiple other landslide hazard assessment methodologies that make use of alternative datasets than those used in this methodology. Methodologies also exist that can assess seismic-induced and rain-induced landsliding separately. However, for the purposes of the PML assessment, the described methodology was considered to be appropriate for assessing risk to buried infrastructure for the district scale of the study, and made use of the available data. Although the normalised different approach does consider all landslide triggering methods, it is considered that material that is susceptible to landslide from climatic triggers, would also be susceptible to move during a seismic event and therefore is appropriate for assessing co-seismic landsliding damage for buried infrastructure assets.

Co-seismic landsliding has been highlighted both in historic events and in predictive modelling to cause substantial damage, financial losses and outages. Future events will not only have direct consequences, but indirect as shown from the Kaikoura earthquake. This illustrates the benefit of conducting regional scale landslide hazard and risk assessment, applying a methodology such as the one presented here. Through an understanding of the hazard and subsequent risk, it allows risk mitigation strategies to be considered and how damage and outages can be reduced. While the seismic-induced landslide hazard assessment methodology presented here has been applied for loss modelling, output from the same methodology could be applied to other uses such as land-use planning, asset management, and emergency response.

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## REFERENCES

- Benn, J. L. 2005. Landslide events on the west coast, South Island, 1867–2002. *New Zealand Geographer*, 61(1), 3-13.
- Callan, J. 2010. *The day the earth moved in Inangahua - 24/05/1998*. [online] Available at: <https://www.gns.cri.nz/Home/News-and-Events/Media-Releases/Inangahua-quake> [Accessed 24 June 2018].
- Cubrinovski, M., Hughes, M., Bradley, B.A., Noonan, J., Hopkins, R., McNeill, S. and English, G., 2014. Performance of horizontal infrastructure in Christchurch city through the 2010-2011 Canterbury earthquake sequence.
- Cousins, W.J., 2013. *Wellington without water: impacts of large earthquakes*. Wellington, New Zealand: GNS Science.
- Dowrick, D.J., 1994. Damage and intensities in the magnitude 7.8 1929 Murchison, New Zealand, earthquake. *Bulletin of the New Zealand National Society for Earthquake Engineering*, 27(3), pp.190-204.
- Dowrick, D.J. and Rhoades, D.A., 2010. A Distributed-Source Approach to Modelling the Spatial Distribution of MM Intensities Resulting from Large Crustal New Zealand Earthquakes. *Bulletin of the New Zealand Society for Earthquake Engineering*, 43(2), pp.85-109.
- Douglas, J.S., 1968. Inangahua Earthquake, 1968. Damage to State Highways. *Bulletin of the New Zealand Society for Earthquake Engineering*, 1(2).
- Flentje, P.N., Miner, A., Whitt, G. and Fell, R., 2007. Guidelines for landslide susceptibility, hazard and risk zoning for land use planning. *Journal and News of the Australian Geomechanics Society*, 42(1).
- GeoNet. (2016). New Zealand catalogue of earthquakes. Retrieved November 2016, from <http://info.geonet.org.nz/display/appdata/Earthquake+Catalogue>
- Hancox, G.T., Perrin, N.D. and Dellow, G.D., 2002. Recent studies of historical earthquake-induced landsliding, ground damage, and MM intensity in New Zealand. *Bulletin of the New Zealand Society for Earthquake Engineering*, 35(2), pp.59-95.
- Hughes, M.W., Nayerloo, M., Bellagamba, X., Morris, J., Brabharan, P., Rooney, S., Hobbs, E., Wooley, K. and Hutchison, S., 2017. Impacts of the 14th November 2016 Kaikōura Earthquake on three waters systems in Wellington, Marlborough and Kaikōura, New Zealand: Preliminary observations. *Bulletin of the New Zealand Society for Earthquake Engineering*, 50(2), pp.306-317.
- McSaveney, E.R., 1982. Recent geomorphic changes in the Bealey, Otira, Mingha, and Deception valleys, Arthur's Pass National Park. *Report for National Parks Authority of New Zealand, Wellington*.
- Opus, 2005. Seismic Risk in the Otago Region, Otago Regional Council Study Report. SPT: 2004/23, 5C0656.00.
- Robinson, T.R., 2018. Road impacts from the 2016 Kaikōura earthquake: an analogue for a future Alpine Fault earthquake?. *New Zealand Journal of Geology and Geophysics*, pp.1-9.
- Robinson, T.R., Buxton, R., Wilson, T.M., Cousins, W.J. and Christophersen, A., 2015. *Multiple infrastructure failures and restoration estimates from an Alpine Fault earthquake: Capturing modelling information for MERIT*. GNS Science.
- Tonkin + Taylor. 2013a. *Quantitative Landslide Risk Assessment Whakatāne and Ōhope Escarpments*. T&T Ref: 28273
- Tonkin + Taylor 2013b. *Quantitative Landslide Risk Assessment Matata Escarpment*. T&T Ref: 29115
- Turnbull, I.M., 2000. Geology of the Wakatipu Area. Institute of Geological & Nuclear Sciences 1: 250,000 Geological Map 18. *Institute of Geological & Nuclear Sciences Limited. Lower Hutt, New Zealand, 1*.