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Liquefaction assessment of highway networks using geospatial models

A. Lin & L. Wotherspoon
The University of Auckland, Auckland, New Zealand

D. Blake, B. Bradley & J. Motha
University of Canterbury, Christchurch, New Zealand

ABSTRACT: Assessment of liquefaction hazard across infrastructure networks using in-situ investigation data and simplified liquefaction evaluation procedures can be costly due to the volume of data required. In these cases, geospatial methods can be used as an alternative approach. This paper applies a geospatial methodology to assess the liquefaction susceptibility of New Zealand's State Highways, allowing for quantification of the overall exposure of this network. Ground motion simulation was used to assess the probability of liquefaction for an Alpine Fault earthquake across the South Island of New Zealand, and, in conjunction with indicators for infrastructure criticality, suggested that areas with the highest liquefaction probability during an Alpine Fault earthquake may have significant local impacts, but only minor impacts on the wider network across the South Island. Using this proof of concept, a wider suite of earthquake scenarios will be used in combination with criticality frameworks to inform wide scale national infrastructure liquefaction assessment.

1 INTRODUCTION

Liquefaction during seismic events can lead to significant damage to buildings and infrastructure networks, including differential settlement of buildings, distortion of roads, or breakage of buried infrastructure (Mian et al. 2013). Because of the country's young coastal sediments and its location along the seismically active Pacific Ring of Fire, New Zealand is prone to liquefaction. During the 2010-2011 Canterbury earthquake sequence, liquefaction and lateral spreading caused substantial damage to the built environment affecting around 60,000 residential houses and major parts of the urban infrastructure systems (Cubrinovski 2013).

An effective resource to identify areas of risk and to estimate the potential extent of liquefaction damage are hazard maps. However, obtaining the required information on soil characteristics to develop these maps usually requires extensive investigations using in-situ methods, such as the Standard Penetration Test (SPT) or the Cone Penetration Test (CPT), and simplified liquefaction evaluation procedures (Boulanger & Idriss 2014; Zhu et al. 2017). When assessing distributed infrastructure networks, the number of investigations required can be expensive and labour-intensive, hence they may not be suitable for the overall assessment of large-scale networks. In this case, geospatial methods combined with probabilistic evaluation can be used as an alternative approach. Zhu et al. (2015) developed and updated (Zhu et al. 2017) a liquefaction model based on geospatial datasets, such as slope, elevation and distance to a water body. As the aim of this approach was to create a tool for rapid estimation of liquefaction extent in order to support disaster response and emergency planning, only datasets which were easily accessible prior to any event were considered.

This paper focuses on the application of geospatial models to assess the liquefaction exposure of State Highways in the South Island of New Zealand. For this purpose, a two-stage analysis has been carried out: First, a susceptibility map was created to show the general vulnerability of the network. Second, ground shaking data from an Alpine Fault earthquake scenario on the South Island was incorporated into the assessment to estimate the probability of liquefaction damage for this specific event. These outputs are discussed and linked with several indicators for infrastructure criticality, such as movement of people, to evaluate the consequences of liquefaction damage to the economy and society. The combination of both exposure and criticality assessment provides a multi-disciplinary understanding of potential liquefaction impacts to inform decision making, with further research needed to characterise the framework for infrastructure criticality aspects.

2 NEW ZEALAND STATE HIGHWAYS

The functionality of national infrastructure networks is essential to provide services such as transportation of people and goods, as well as electricity supply. Because of their geographic distribution, infrastructure networks are often exposed to a range of natural hazards. In New Zealand, another important factor is the rugged topography and limited network redundancy across much of the country, meaning that disruption in one location can often have widespread implications across the network. In the event of an earthquake, liquefaction induced lateral spreading and ground deformation are one of the main causes of infrastructure damage. Impacts can vary from superficial changes, which do not interfere with the network's functionality, to total failure of the system components and subsequent widespread outages (Mian et al. 2013; Ministry of Business, Innovation & Employment 2017).

Facing a growing population, increasing freight transport and tourist travel needs, the State Highway network is New Zealand's most valuable asset being worth NZD 26 billion (NZ Transport Agency 2018a). It represents only 12% of the entire road system, but accounts for up to 50% of all motor vehicle travel distance and facilitate long distance trips across the country (Ministry of Transport 2011). For national freight movement, State Highways remain the primary transport mode covering 91% of cargo handling (measured by freight tonnes). Compared to rail and coastal shipping, they are more cost efficient and provide flexibility as well as accessibility in terms of space and time (Ministry of Transport 2014).

3 GEOSPATIAL LIQUEFACTION MODEL

The Zhu et al. (2017) geospatial model relies on a set of 18 variables which are related to factors most relevant to liquefaction: soil properties (relative density), water table depth (saturation), and ground shaking (load). To correlate these variables with liquefaction occurrence, case history data from 22 different earthquakes in the United States, New Zealand and Asia were obtained. Five events where liquefaction did not manifest within the same areas were also assessed to account for low intensity shaking events, in which liquefaction is unlikely to occur. Since most liquefaction manifestation has been observed in coastal areas, the primary model was biased, making it less applicable to non-coastal regions. Therefore, a modified version with a different arrangement of variables was introduced for global implementation (Zhu et al. 2015; Zhu et al. 2017).

For relative density and saturation, the best-performing variables were slope-derived V_{S30} (time averaged shear-wave velocity over the first 30m), water table depth, distance to coast, distance to river, distance to closest water body, and precipitation. Peak ground velocity (PGV) proved to be most suitable for characterizing ground shaking intensity. Interaction effects among variables, for instance between distance to coast and distance to rivers, were also considered and improved the overall performance of the model (Zhu et al. 2017).

Comparing the predictions of both models with the actual observations showed several discrepancies, revealing the limitations of the Zhu et al. (2017) approach. One reason for inaccurate results was the fact that site specific characteristics and other contributing factors (e.g. soil plasticity) were not included due to their restricted accessibility. Beyond that, the global model did not perform as well as the regional (coastal) model, indicating that variables related to soil saturation were the driving factor for liquefaction occurrence. Despite its limitations, the model of Zhu et al. (2017) provides useful results, especially considering the cost and time required to collate traditional in-situ methods across such a broad area (Maurer 2017). It is therefore a reasonable tool to assess liquefaction on a national scale and to estimate potential liquefaction induced damage of New Zealand's State Highway network.

3.1 *Application to the State Highway network*

In order to apply the approach of Zhu et al. (2017) and to perform the assessment, the first step involved the geospatial modelling of the State Highway network in ArcGIS using a publically available dataset from the NZ Transport Agency (2012) (Figure 1a). Since values for liquefaction susceptibility and probability were calculated for specific points, the format of the State Highway data set (polylines) needed to be adjusted by splitting the lines into sections of 100m and identifying centre points for each section. The spacing of 100m allows a detailed South Island-wide analysis of geospatial characteristics without creating issues regarding the data volume.

Liquefaction susceptibility was calculated for each data point using the geospatial proxies described in the previous section. However, instead of the global slope-derived Vs30 variable, a recently developed New Zealand-specific Vs30 model (currently unpublished) was used. In order to calculate the probability of liquefaction occurrence and to estimate the potential damage, ground shaking data for a modelled Alpine Fault earthquake (rupture propagating northwards) was used. The Alpine Fault is a 600km long fault on the South Island which marks the boundary of the Pacific and Australian plates. According to recent studies of historic data, there is 30% chance that the Alpine Fault will rupture in the next 50 years (Berryman & Cochran 2012, Howarth et al. 2018). Because of the severe consequences, ground shaking scenarios along the Alpine Fault have become a frequently discussed topic in current research, e.g. Sutherland et al. (2007), Cox et al. (2012) and Orchiston et al. (2018), and were used as a showcase event to estimate liquefaction probability in this paper. However, considering that the extent of the fault ruptures is not entirely predictable and that the potential

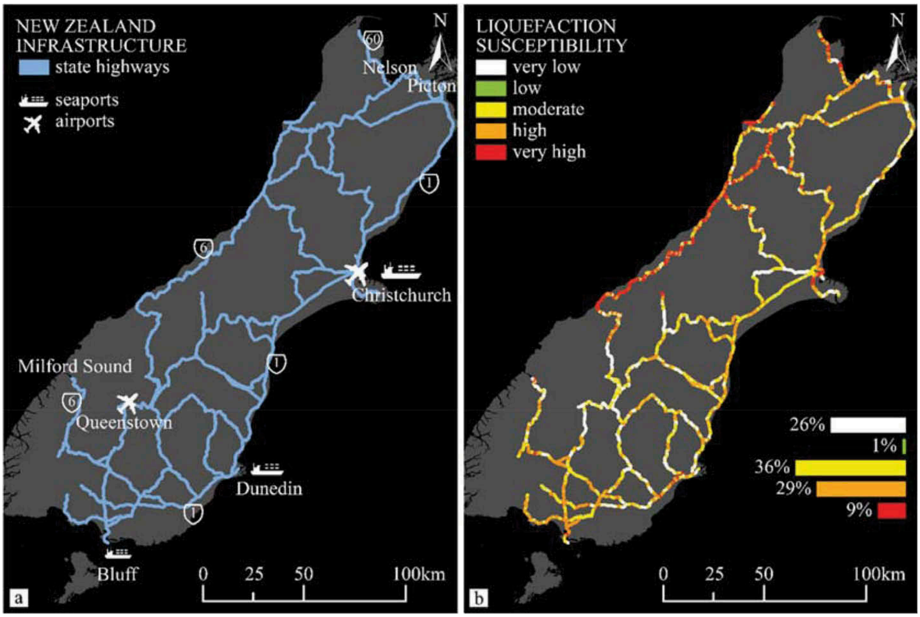

Figure 1. (a) New Zealand state highway network (South Island) including locations of major cities, airports and seaports. (b) Liquefaction susceptibility based on the geospatial model of Zhu et al. (2017).

impact is based on simplified estimation procedures, the outcome has to be interpreted with caution – the actual degree of liquefaction impact could be higher or lower (Bradley et al. 2017; Robinson 2018).

4 LIQUEFACTION EXPOSURE OF THE STATE HIGHWAY NETWORK

Based on the geospatial model, liquefaction susceptibility was defined across the State Highway network (Figure 1b). Following the classification of Zhu et al. (2017), the susceptibility output can be interpreted by introducing the categories very low (white), low (green), moderate (yellow), high (orange), and very high (red). The relatively high percentage of State Highways with moderate to very high susceptibility (74%) is because a large proportion of the network is located close to the coast and across alluvial plain areas. SH 6 along the West Coast shows a large number of segments with very high susceptibilities. Other "hotspot" regions can be observed at the northern coast (SH 60), in the urban area of Christchurch, and in various parts south of Dunedin. Lower susceptibilities are more represented in mountainous terrain where conditions are less favourable for liquefaction, but may increase the amplification of ground shaking or the exposure to other hazards, such as landslides.

Since the susceptibility results do not consider ground shaking, they only characterise the potential for liquefaction of the different soil deposits along the State Highways. In fact, high susceptibility does not necessarily result in high risk. Areas which are classified as highly susceptible, but not prone to strong ground shaking, may be less relevant than areas of low susceptibility with a high exposure to earthquakes (Glassey & Heron 2012). It is therefore essential to link the susceptibility results to ground shaking data, and to estimate the probability of liquefaction for potential scenarios. Figure 2a illustrates the PGV distribution across the State Highway network for an Alpine Fault earthquake with an epicentre in the south and the rupture propagating north along the fault. As expected, very strong ground motion with PGVs of 40.0cm/s and above are found for State Highways close to the Alpine Fault, e.g. SH 6 along the West Coast.

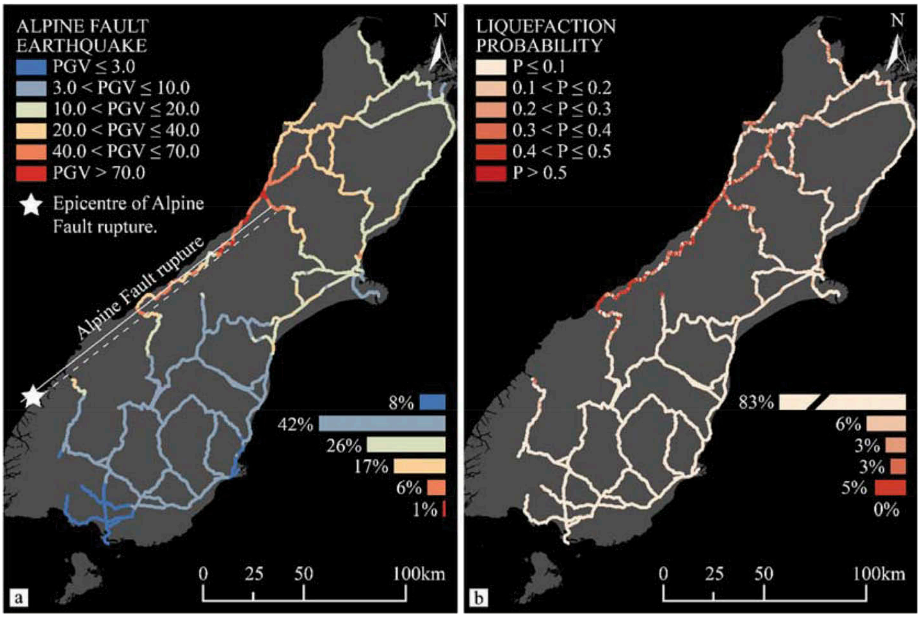

Figure 2. (a) PGV in cm/s of an Alpine Fault earthquake with epicentre located in the South (rupture propagating northwards). (b) Liquefaction probability based on the geospatial model of Zhu et al. (2017).

The lowest PGV results (PGV ≤ 10.0cm/s) can be observed in the south east of the South Island behind the direction of rupture propagation, where around 50% of the State Highways are located. This particularly applies to the areas of Dunedin and Bluff (PGV ≤ 3.0cm/s).

Based on the PGV data for this specific earthquake scenario, liquefaction probabilities were calculated for each State Highway data point (Figure 2b). Zhu et al. (2017) used the categories low (P ≤ 0.3), medium (0.3 < P≤ 0.5) and high probability (P > 0.5) to classify the results. Following this system, none of the State Highways show a high probability of liquefaction. However, around 8% fall into the medium range; especially major parts of SH 6 along the West Coast that have probabilities of 0.4 or higher, which is not surprising considering that this area had been identified highly susceptible to liquefaction and strongly affected by the modelled Alpine Fault earthquake. On a more local level, higher probabilities can also be observed in scattered parts of the network, e.g. in Milford Sound, Christchurch or along SH 60 including the connecting State Highways towards SH 6. However, the majority of the State Highway network (92%) shows a low probability of liquefaction occurrence mainly due to their distance away from the main rupture.

The results provide a first insight to the exposure of New Zealand State Highways to liquefaction using a systematic geospatial approach. While the susceptibility map allows a more general evaluation of the network's vulnerability, the probability map can be used to demonstrate the actual extent of potential damage for a specific earthquake. Regarding the accuracy of the estimations, it is important to consider that the results are affected by a range of uncertainties within the geospatial model. Further research has to include more ground shaking scenarios in order to understand the full extent of seismic exposure and to identify damage patterns across the State High-way network, and assessment of the accuracy of the geospatial models for regional soil deposits. Regardless of the limitations concerning the accuracy of the results, this paper uses the outcome as an example to describe the general process of liquefaction impact assessment. Through the use of a range of scenarios, locations that are repeatedly exposed to high probabilities of liquefaction can be further assessed using more site specific methods.

5 POTENTIAL IMPACTS OF LIQUEFACTION ON NETWORK PERFORMANCE

Partially or fully damaged infrastructure can have a diverse range of consequences on the economy and society. Some networks are more significant than others, making infrastructure criticality an important factor for the evaluation of the potential impact of liquefaction induced damage. Different approaches have been established which outline the criticality of general roads, e.g. the One Road Network Classification (ORNC) by the NZ Transport Agency (2013). Most of the indicators introduced in this framework rely on the movement of people or goods and can be applied to the State Highway network. In this section, we adopt ORNC indicators to describe State Highway criticality; our evaluation is limited to a qualitative analysis and does not include the classification of the flow-on impacts of the wider network, which would require a more detailed assessment.

5.1 *Movement of people*

A common indicator to measure the movement of people on State Highways is the number of vehicles. Figure 3a shows the average annual daily traffic (AADT) across the South Island for 2017 based on monitoring sites from the NZ Transport Agency (2018b). Most State Highways (67%) have a traffic volume of less than 3,000 vehicles per day; they are mainly located on the West Coast and in the central area of the South Island. The highest traffic volumes (AADT > 10,000) can be found in densely populated places, such as Christchurch and Dunedin, as well as tourist hotspots, such as Queenstown and Nelson.

Another indicator to quantify movement of people is the proximity to airports. In this context, State Highways can be assigned to passenger numbers of the airport they provide access to. For example, access to Christchurch International Airport – the busiest airport in the

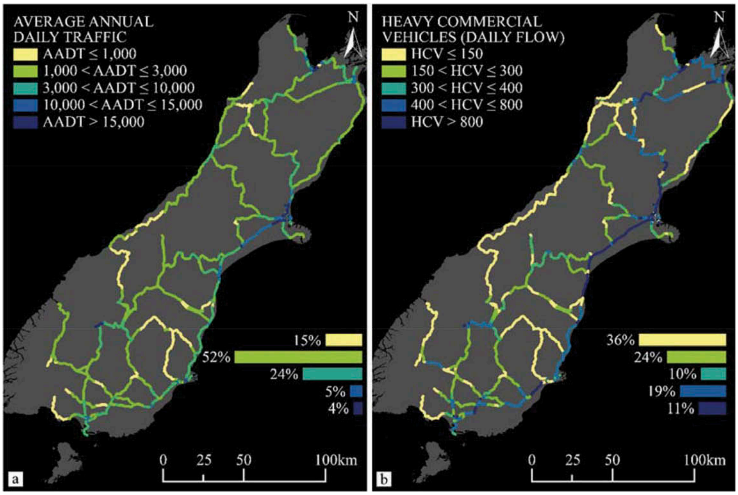

Figure 3. (a) Average annual daily traffic (AADT) in 2017. (b) Daily flow of heavy commercial vehicles (HCV) in 2017.

South Island – is given by SH 1 as well as the connecting State Highways between Christchurch and the West Coast (Christchurch Airport 2017). Other important airports are Queenstown Airport and Nelson Airport; both are primary hubs for tourists.

Considering these two indicators, the high probability of liquefaction damage for SH 6 along the West Coast appears to have a comparatively low impact, because a smaller volume of traffic would become affected. However, given that this State Highway section lacks any alternative routes, post-event emergency access issues makes this route more significant irrespective of the amount of people being affected. The indicators also lead to the conclusion that damage to State Highways around dense populations, such as Christchurch, would severely impair the movement of people, making these parts of the network more critical. Christchurch, Nelson and parts of Dunedin show susceptibility rates in the moderate to very high category (Figure 1b), and thus, have the potential to experience liquefaction induced damage. Further research will include the assessment of other earthquake scenarios to evaluate liquefaction exposure and potential damage in these areas.

5.2 *Movement of goods*

Another potential indicator for movement of goods is the number of heavy commercial vehicles (HCV). Figure 3b illustrates the daily flow of HCV based on the same monitoring data provided by the NZ Transport Agency (2018b). Similar to Figure 3a, a high daily flow can be observed around populated areas, especially on SH 1 between Christchurch and Dunedin. In addition, a large number of heavy commercial vehicles uses the State Highways around Picton harbour, a vital link to the North Island (Cook Strait). Especially the northern extension of SH 1 appears critical considering it is the only connection to the port.

As a second indicator, freight volume and freight value can be assigned to the State Highways linking the seaports to the rest of the network. While freight volume in the broader sense is already represented by the daily flow of heavy commercial vehicles, freight value adds a new dimension to the impact assessment. Again, Christchurch plays an important role: Lyttelton Port Company is the leading seaport on the South Island according to cargo weight (5.5 million tonnes) and cargo value (8.9 billion NZD), underlining the high criticality of the surrounding State Highways. After Christchurch, Port Chalmers in Dunedin (3.8 billion NZD) and Port Bluff (1.9 billion NZD) are the seaports with the highest freight value on the South Island, making their connecting State Highways critical assets as well (Ministry of Transport 2017a, b).

Similar to the observations of the previous section, liquefaction along SH 6 seems to have a relatively low impact on the movement of goods, while other State Highways like SH 1 are crucial to the freight transport between cities and ports. However, at a local scale, the loss of road access can have a significant impact on the industries and businesses in the area (which are also affected by the potential of landslides). This is another factor that needs to be taken into account in relation to regional criticality versus national criticality of these routes. Due to an increased liquefaction susceptibility along these State Highways, again other earthquake scenarios are being assessed to add into the assessment for further research.

6 DISCUSSION

Using the geospatial model of Zhu et al. (2017) enabled the development of a liquefaction hazard map for New Zealand State Highways. The susceptibility analysis showed very high values along the West Coast (SH 6) and in parts of Christchurch as well as Dunedin. Based on the ground shaking data of an Alpine Fault earthquake scenario, the highest liquefaction probabilities were evident along the West Coast (SH 6). Based on the exposure assessment alone, this section appears to be most at risk in terms of potential damage. However, considering criticality factors, such as daily traffic or proximity to airports, illustrates the significance of undertaking a wider impact assessment. Despite its relevance for tourism and primary industries, and its lack of redundancy, the evaluation of SH 6 indicates low criticality in comparison to other parts of South Island's State Highway network. High criticality can be identified for State Highways in populated areas (e.g. Christchurch) and locations of economic interest (e.g. Picton).

Further research needs to link the two components – liquefaction likelihood and infrastructure criticality – and to consider the vulnerability of the State Highway network to liquefaction in order to expand the focus from a hazard to a risk analysis, and to understand which parts of the network may be in need of investment to improve their performance. In this context, the following aspects should be taken into consideration: First, additional ground shaking data from a range of potential earthquake scenarios needs to be included to more rigorously assess the wider network; this will improve the assessment of State Highways which are both susceptible to liquefaction and critical. Second, a systematic approach to quantify infrastructure criticality has to be developed specifically for the State Highway network. Economic indicators (e.g. movement of people and goods) may be most suitable; however, social factors (e.g. emergency routes and access to critical facilities) should also be considered. Third, other infrastructure networks, such as rail and electricity transmission, should to be integrated to the overall assessment, since earthquakes often affect multiple infrastructure systems. This would also require the identification and evaluation of interdependencies and alternative transport modes.

Taking these factors into account, the concepts described in this paper can be used to support decision making regarding infrastructure investment, rapid response and emergency planning, as well as prioritization of post-earthquake reconstruction projects.

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