Multi-scenario approach for the assessment of liquefaction exposure across New Zealand State Highways

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ABSTRACT

Events such as the 2010–2011 Canterbury Earthquake Sequence or the 2016 Kaikōura earthquake demonstrated the impacts of liquefaction and lateral spreading across New Zealand infrastructure networks. Based on the ground shaking intensity of 478 actual and hypothetical earthquake scenarios, this paper introduces a new approach for the estimation of the liquefaction exposure across the State Highway network, using the number of events (NoE) that might trigger liquefaction along the network. The multi-scenario approach differs from other methods, such as return period assessments, as it considers ground shaking as an aggregated hazard rather than a probability, which helps identifying network sections that could be repeatedly affected during earthquakes. The results are presented in a hazard map, demonstrating the highest liquefaction exposure in Whakatāne (Bay of Plenty) with State Highways being affected by liquefaction during 37 out of 478 earthquake events. Increased exposure is also observed along State Highways in Napier (NoE $\leq$ 26) and Wellington (NoE $\leq$ 24). Limitations arise from the fact that the geospatial model does not account for subsurface soil characteristics and that aspects regarding the network vulnerability are not considered in the assessment. Future research should also investigate linking the exposure results to indicators of network criticality (e.g. number of vehicles, or freight value) to better quantify the impact of liquefaction manifestation. The framework is adaptable to other infrastructure networks and can be used to support decision making processes regarding hazard mitigation or preparedness for future earthquakes.

1 INTRODUCTION

New Zealand infrastructure networks are exposed to a range of natural hazards, including liquefaction and lateral spreading. Events like the 2010–2011 Canterbury Earthquake Sequence demonstrated the potential impacts (Cubrinovski et al., 2012), varying from superficial damage, which does not interfere with the network's functionality, to total failure of the system components and subsequent widespread outages.

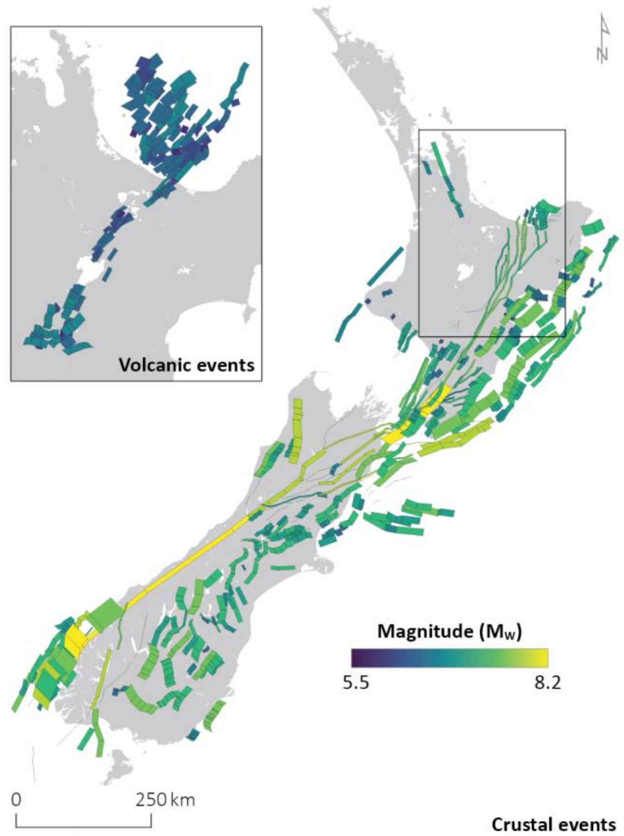

Figure 1. Location of the faults for the 478 seismic events including moment magnitude (M_W).

This paper introduces a new approach for the estimation of liquefaction exposure across the State Highway network. Using a New Zealand-specific liquefaction model, the liquefaction probability is calculated for 478 earthquake scenarios. For each State Highway segment, liquefaction exposure is measured by counting the number of events (NoE) that are expected to result in liquefaction manifestation. Compared to the evaluation of a specific earthquake scenario or a specific return period, the multi-scenario approach helps to identify network sections that could be affected by multiple earthquake sources. The results are presented in a hazard map with a more detailed evaluation of State Highways that show high exposure. Limitations and uncertainties related to the multi-scenario approach as well as potential areas for further research are discussed.

2 SEISMIC EVENTS

The ground motion data for the seismic events investigated in this paper is based on Cybershake NZ v19.5, the simulation-based probabilistic seismic hazard analysis (PSHA) for New Zealand (Bradley et al., 2020). The source rupture geometries are retrieved from Stirling et al. (2012) using geologic data and case histories from previous earthquakes to simulate the ground motion of actual and potential fault ruptures.

A total of 478 PSHA fault ruptures potentially affect the State Highway network; hence, are considered for the estimation of the liquefaction assessment. Figure 1 presents the surface projection of these faults including the tectonic type and the moment magnitude (M_W). The majority (69%) are active shallow crustal ruptures with a maximum M_W of 8.2 (average M_W = 7.1). The remaining faults (31%) describe shallow crustal earthquakes in volcanically active regions with a maximum M_W of 6.8 (average M_W = 6.4). While most crustal events (65%) are onshore and scattered across both the North and the South Island of New Zealand, all volcanic events are restricted to the North Island.

3 GEOSPATIAL LIQUEFACTION MODEL

Considering the areal extent of the State Highway network and the large number of seismic events, a probabilistic approach based on geospatial data is the most efficient method to calculate the liquefaction probability. This paper uses a modified version of the global geospatial liquefaction model developed by Zhu et al. (2017). Using logistic regression, Zhu et al. (2017) correlated observational data from 27 earthquakes around the globe with geospatial data on the soil properties that are related to liquefaction manifestation. They found that the most promising results were achieved with a combination of peak ground velocity (PGV) in cm/s, shear wave velocity in the upper 30 m (Vs30) in m/s, annual precipitation (PRECIP) in mm, distance to the closest water body (DW) in km and water table depth (WTD) in meters below ground level (m. b. g. l.).

The liquefaction probability (P) is calculated by the equation

$$P = 1/(1 + \exp(-X))) \quad (1)$$

where X equals a function of the explanatory variables

$$X = 8.801 + 0.334 \ln(PGV) - 1.918 \ln(Vs30) + 5.408\ 10^{-4}\ PRECIP - 0.2054\ DW - 0.0333\ WTD \quad (2)$$

For PGV below 3 cm/s, PGA below 0.1 g, or Vs30 above 620 m/s, no liquefaction manifestation is expected (P = 0) (Rashidian & Baise, 2020; Zhu et al., 2017). In addition, PRECIP is restricted to a maximum of 1700 mm and a magnitude scaling factor (MSF) is applied to low-magnitude earthquakes (M < 6) to reduce overprediction (Rashidian & Baise, 2020).

P describes the likelihood of liquefaction manifestation in a specific location but does not indicate the liquefaction manifestation type (e.g. cracking versus lateral spreading) or severity (e.g. minor versus severe). Moreover, as a geospatial approach, the liquefaction model does not account for important soil characteristics (e.g. interbedded layers with different liquefaction potential) or seismic conditions (e.g. preceding earthquakes), which might lead to discrepancies in the model outcome.

Lin et al. (2021) and Lin et al. (2022) modified the Zhu et al. (2017) model by replacing the global variables for Vs30, DW and WTD with New Zealand-specific datasets without changing the coefficients in Eq. (2) (see DATA section at the end of this paper for further details including data references). Evaluating the modified model for the 2010–2011 Canterbury Earthquake Sequence and the 2016 Kaikōura earthquake indicated improved prediction performance due to higher resolution (200 m) and / or more accurate information of the New Zealand-specific datasets. Results also suggested that liquefaction manifestation can be expected for P of 46% or above. This probability threshold allows for a binary prediction outcome; for example, whether a State Highway section is affected by liquefaction manifestation during an earthquake scenario.

4 NEW ZEALAND STATE HIGHWAYS

The State Highway network is New Zealand's most valuable asset worth NZD 52 billion; it represents only 12% of the overall road system but accounts for 70% of freight and 55% of vehicle travel and remains the primary transport mode for infra-regional freight movement (NZTA, 2021). Figure 2 presents the New Zealand State Highway network, including locations of interest, such as major cities as well as air- and seaports. The State Highway network is categorized using the One Network Road Classification (ONRC), a framework developed by Waka Kotahi NZ Transport Agency to support managing road activity and decision making regarding infrastructure investment in New Zealand (NZTA, 2013). The ONRC accounts for factors, such as annual average daily traffic (AADT), heavy commercial vehicles (HCV) or population linked to the network, and can be used to quantify the socio-economic importance of a State Highway.

Because of their geographic distribution, the State Highways are exposed to a range of natural hazards including earthquakes and earthquake-triggered liquefaction. Events such as the 1931 Napier earthquake (Dowrick, 1998), 1978 Edgecumbe earthquake (Pender & Robertson, 1987), and the 2010–2011 Canterbury Earthquake Sequence (Cubrinovski et al., 2012) have demonstrated the social and economic consequences of network disruptions, emphasizing the need to better understand liquefaction hazards across the State Highway network.

In order to estimate the liquefaction exposure, the line data representing the State Highways (NZTA, 2018) is split into segments of 100 m. For each seismic event, liquefaction probability is calculated in the centrepoint

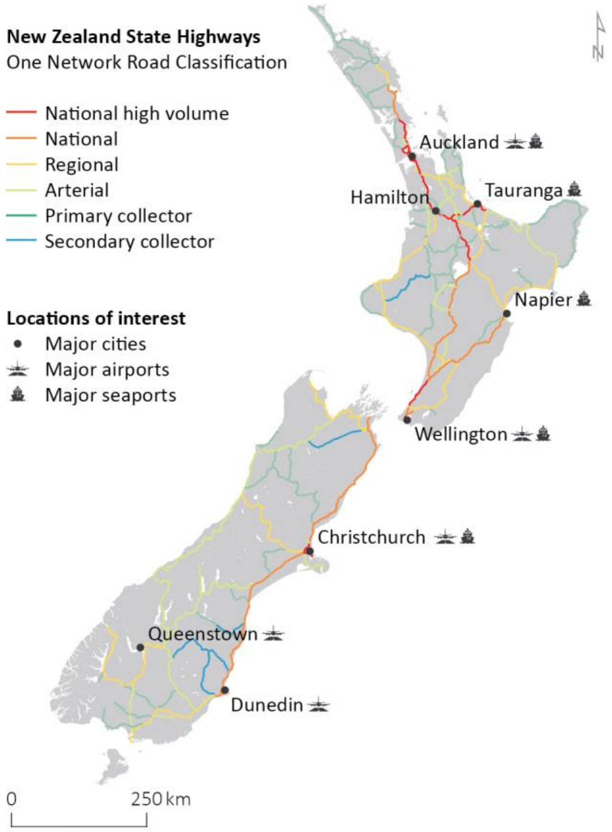

Figure 2. New Zealand State Highways categorized according to the One Network Road Classification.

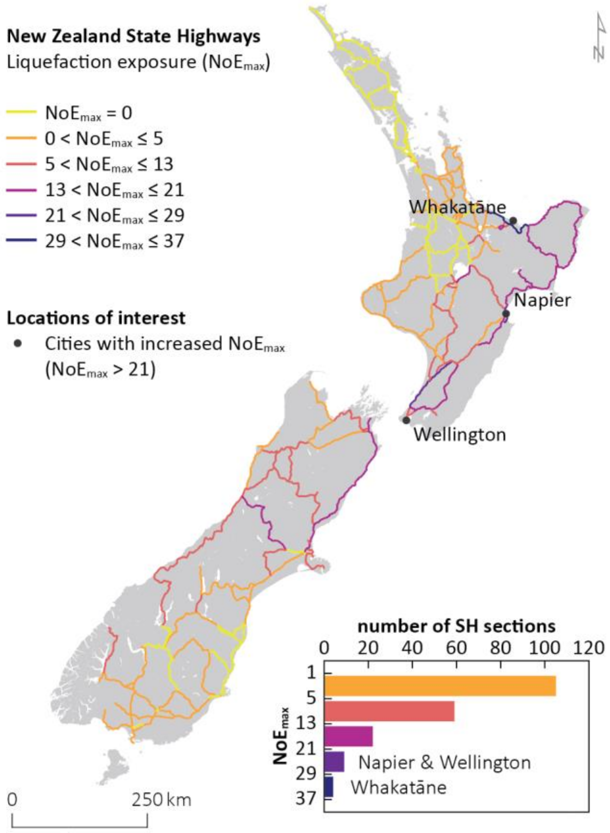

Figure 3. Liquefaction exposure (NoE_{max}) across the New Zealand State Highway sections.

of the network segments. The number of events (NoE) that are expected to result in liquefaction manifestation ($P \geq 0.46$) is used to represent the exposure. To better reflect the network as a system of nodes and links, the segments are converted to sections by dissolving the segments between two intersections of the State Highway network. Liquefaction manifestation in any location affects the entire section as it potentially disrupts the link between the two nodes (intersections). The maximum NoE (NoE_{max}) of each section is used to compare the results across the State Highway network.

5 RESULTS

Figure 3 presents the NoE_{max} across the New Zealand State Highway network. 83% of the State Highways (measured by length) result in a NoE of 0, indicating that most of the network is not affected by liquefaction manifestation during any of the 478 earthquakes. In general, the spatial distribution of the NoE_{max} reflects the location of the faults (Fig. 1). As a result, the northwest of the North Island as well as the southeast of the South Island lead to very low values.

The highest NoE_{max} is observed in Whakatāne (Fig. 4) (90 km east of Tauranga), where State Highway 30 is estimated to be affected by earthquake-induced liquefaction in 37 scenarios. The sections of State Highway 2 linking Whakatāne to the wider network also present high NoE_{max} values as a result of being exposed to numerous potential fault ruptures. The Whakatāne region is considered very susceptible to liquefaction due

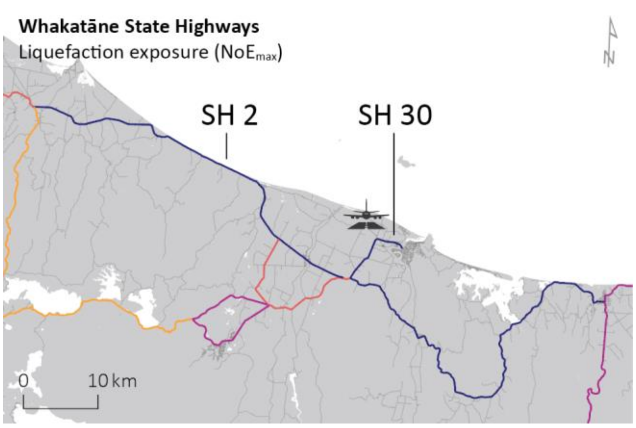

Figure 4. Liquefaction exposure (NoE_{max}) across the New Zealand State Highway sections in Whakatāne. See legend in Fig. 2 and Fig. 3 for symbology.

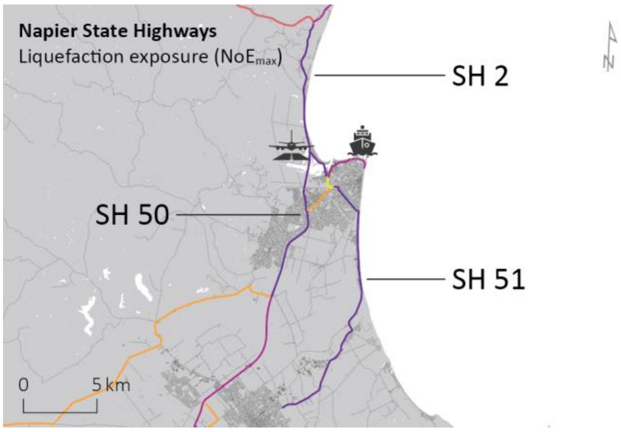

Figure 5. Liquefaction exposure (NoE_{max}) across the New Zealand State Highway sections in Napier. See legend in Fig. 2 and Fig. 3 for symbology.

to the low elevation (shallow water table) and the presence of alluvial deposits (Bastin et al., 2020). This became evident during the 1978 Edgecumbe earthquake, which caused severe liquefaction and lateral spreading along the rivers of Whakatāne, damaging buildings and roads (Pender & Robertson, 1987).

Increased exposure is also found in Napier (Fig. 5) with NoE_{max} up to 26 (SH 2). Both the north- and south-bound State Highways, connecting the city to the wider network, present higher values of up to 25. In addition, a short section of the State Highway providing access to the port (SH 50) as well as a longer stretch along the east coast show NoE_{max} between 19 and 22, which suggests that most of the State Highways in this region are likely to be exposed to liquefaction hazards. As all major access roads to Napier show high exposure, it can be expected that earthquakes in this region, causing liquefaction-induced damage to the State Highways, could affect the post-event access to the city.

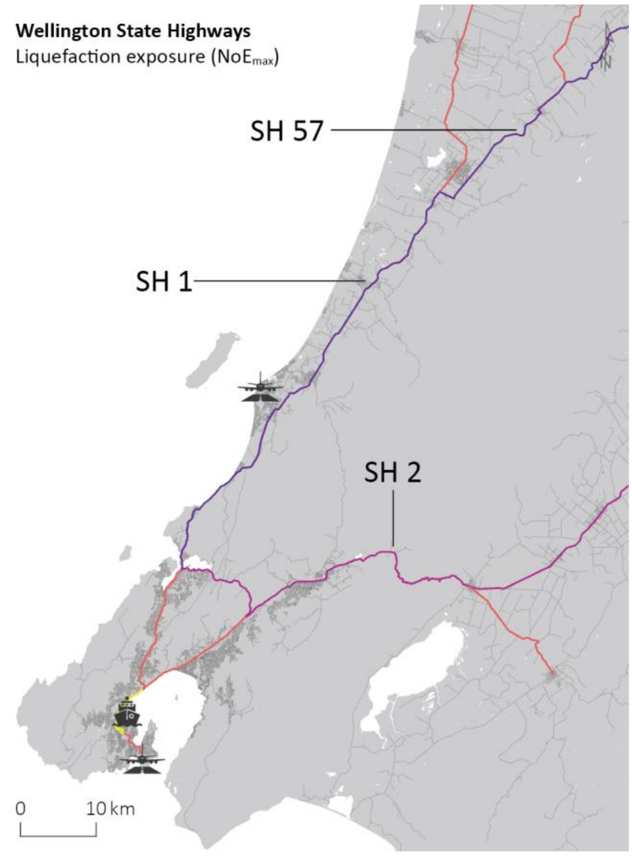

Figure 6. Liquefaction exposure (NoE_{max}) across the New Zealand State Highway sections in (Greater) Wellington. See legend in Fig. 2 and Fig. 3 for symbology.

Similar to the Whakatāne region, Napier is located across sedimentary deposits, indicating higher susceptibility to liquefaction (El Kortbawi et al., 2019). In addition, the area is exposed to multiple crustal faults (Fig. 1). The 1931 Hawke's Bay earthquake was one of the most damaging earthquakes in New Zealand's history and demonstrated the impacts of the liquefaction and lateral spreading across Napier, causing substantial damage to road and rail bridges (Dowrick, 1998).

Across Greater Wellington (Fig. 6), various sections of the State Highway network show higher NoE_{max} (e.g. SH 57: NoE_{max} = 24). State Highway 1 and 2, which provide access to (metropolitan) Wellington, present different levels of liquefaction exposure with values ranging from 0 to 22. Aside from the proximity to the faults, the increased NoE_{max} values are likely due to the high susceptibility, which results from saturated alluvial soil and sediments along the west coast (SH 1) and across the Wairarapa Valley (SH 2) (Hancox, 2005). Historic earthquakes demonstrated the high exposure of these regions to liquefaction and lateral spreading. One example is the 1855 Wairarapa earthquake, which is considered the strongest recorded earthquake in New Zealand, causing extensive ground damage (e.g. cracking) across of State Highway 2 (Butcher, 2005; Fairless & Berrill, 1984). Although the sections in metropolitan Wellington present relatively low values (NoE_{max} = 7), areas such as the reclaimed land at Centreport, which connects to State Highway 1, are considered highly susceptible (Dellow et al., 2018; Dhakal et al., 2020) and might be more relevant for the assessment of a (region) specific event.

6 DISCUSSION AND CONCLUSION

Liquefaction exposure was calculated across the New Zealand State Highways using the probability estimates of 478 actual and hypothetical earthquake scenarios, allowing for the identification of network sections that could be repeatedly affected during earthquakes. While providing a new perspective on the liquefaction hazard, there are limitations and uncertainties that need to be considered when applying the multi-scenario approach to other networks. For instance, the geospatial model does not account for soil or ground related processes affecting the surface manifestation, which contribute to the severity and extent of potential network damage. In this context, it is also important to account for the network vulnerability, which determines the level of service and the time of disruption caused by the repair works. For example, liquefaction manifestation does not necessarily lead to road damage and / or requires extensive repair work in order to restore services. This was demonstrated during the 2010–2011 Canterbury Sequence when almost all road bridges were in service immediately or shortly after the earthquakes despite showing low to moderate damage (Cubrinovski et al., 2014). In relation to post-event network functionality, factors such as alternative routes should also be taken into consideration to better represent the spatial interconnectivity of the State Highway network.

To better estimate the potential impacts of liquefaction manifestation across the State Highway network, further research needs to link the exposure results to indicators of network criticality. Although the State Highways in Whakatāne lead to the highest NoE_{max} (Fig. 4), their socio-economic relevance according to the ONRC (e.g. SH 30: arterial, Fig. 3) is relatively low. The State Highways in Napier, on the other hand, are more critical (e.g. SH 50: national high volume). Due to high exposure and criticality, the impact might be much more significant in this area. Apart from the ONRC, criticality measures could also consider more specific aspects, such as daily traffic volume or freight value, which present quantitative indicators that may be more practical for comparison.

Despite the need for further improvement, the framework provides an alternative approach to assess liquefaction exposure across New Zealand State Highways as it considers ground shaking as an aggregated hazard rather than a probability (e.g. return period analysis), which helps identifying network sections that might be affected by multiple earthquakes. It can be applied to other networks (e.g. rail or power transmission) and allows for the generation of high-resolution hazard maps, that can be used for both national-scale and local-scale assessments, supporting decision making processes regarding hazard mitigation or preparedness for future earthquakes.

DATA

Apart from PRECIP, which is based on the global weather and climate database WorldClim (Hijmans et al., 2005), all input variables are retrieved from New Zealand datasets. For Vs30, the 100 m resolution map by Foster et al. (2019) is used. DW is defined as the minimum of the distance to the closest river (MfE, 2010, stream order 4 or above) and the distance to the nearest coastline (LINZ, 2012). WTD is based on the 200 m resolution data by Westerhoff et al. (2018).

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