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The past is key to the future; Collating historical cases of liquefaction to supplement liquefaction hazard assessments

S.H. Bastin
Beca Ltd, Christchurch, New Zealand.

S. van Ballegooy
Tonkin & Taylor Ltd, Auckland, New Zealand.

M. Ogden
Tonkin & Taylor Ltd, Nelson, New Zealand.

ABSTRACT

Historical records indicate that consequential liquefaction has occurred during upwards of 11 earthquakes in New Zealand since European settlement and prior to 2010. Post-event observations of land damage have been collated into an online geospatial database that is now publicly available. The dataset outlines areas that have historically liquefied, and thus are susceptible to liquefaction during future events, and may be used to supplement Level A (Desktop) and Level B (Calibrated Desktop) liquefaction hazard assessments as per the MBIE (2017) guidelines. Interrogation of the dataset indicates that liquefaction has primarily occurred in low elevation areas proximal to waterways with 80 percent of the collated reports within 500 m of a river or stream. Comparison of CPT traces in areas where liquefaction was and was not reported following the 2016 Kaikoura earthquake show that liquefaction predominantly manifested in areas containing comparatively thick layers of low relative density silty sands under PGA in excess of ~0.1g. The collated dataset enables calibration of liquefaction triggering assessments against actual observations when combined with estimated ground shaking intensities of the causative earthquake. Comparison of the predicted liquefaction hazard in Whakatane with that observed following the 1987 Edgecumbe earthquake outlines areas of inconsistent prediction. Potential reasons for the over-predictions include interlayering of soil types within distal floodplains and/or back swamp environments, and/or the presence of pumice. It is anticipated that this work will help to characterize settings, and/or geomorphic conditions where liquefaction typically manifests. The collated dataset provides a valuable tool for desktop hazard studies and in the verification of liquefaction hazards as interpreted from simplified analyses.

1 INTRODUCTION

Earthquake-induced liquefaction and associated lateral spreading pose a significant hazard to the built environment. Heightened awareness of the consequences of liquefaction following the 2010-2011 Canterbury earthquake sequence (CES) resulted in a series of guidelines for practicing engineers (i.e NZGS, 2016). Subsequent recommendations made by the Royal Commission of Inquiry into Building Failure caused by the Canterbury Earthquakes resulted in guidance to manage liquefaction related risk in land use planning with a focus on regulatory framework (MBIE, 2017). The guidance outlines approaches for assessing liquefaction hazards at range of scales based on the availability of geotechnical data ranging from a high-level regional assessment down to site-specific analysis. Recommendations for Level A (Desktop) and Level B (Calibrated Desktop) studies involve consideration of geology/ geomorphology, groundwater and seismic hazard, with a qualitative assessment of some geotechnical data required for Level B. Both approaches may be supplemented by historical records of liquefaction however these records are scattered throughout post-event literature so are rarely considered.

Historical records indicate that consequential liquefaction has occurred during upwards of 11 earthquakes in New Zealand since European settlement and prior to the 2010 Darfield earthquake (indicated in Figure 1). Records of ‘ground cracking’ and ‘quicksand’ are often included in newspaper articles, photographs, and diaries following historical earthquakes (i.e. pre-1850’s). These reports are typically held in museum archives and in some cases have been collated and geospatially located to infer distributions of liquefaction (i.e. Fairless and Berrill (1984) and Elkortbawi, (2017). Maps outlining distributions of liquefaction manifestations are available following more recent events, however these are typically scattered throughout post-event publications and technical reports. Fairless and Berrill (1984) previously collated pre-1984 records of liquefaction into a tabular format and produced a New Zealand scale map outlining the spatial distribution of the historical reports. The collated reports indicate that the liquefaction had generally been confined to localized areas proximal to waterways however the map scale does not allow for site-specific interrogation and subsequently the data cannot be readily incorporated into liquefaction hazard assessments.

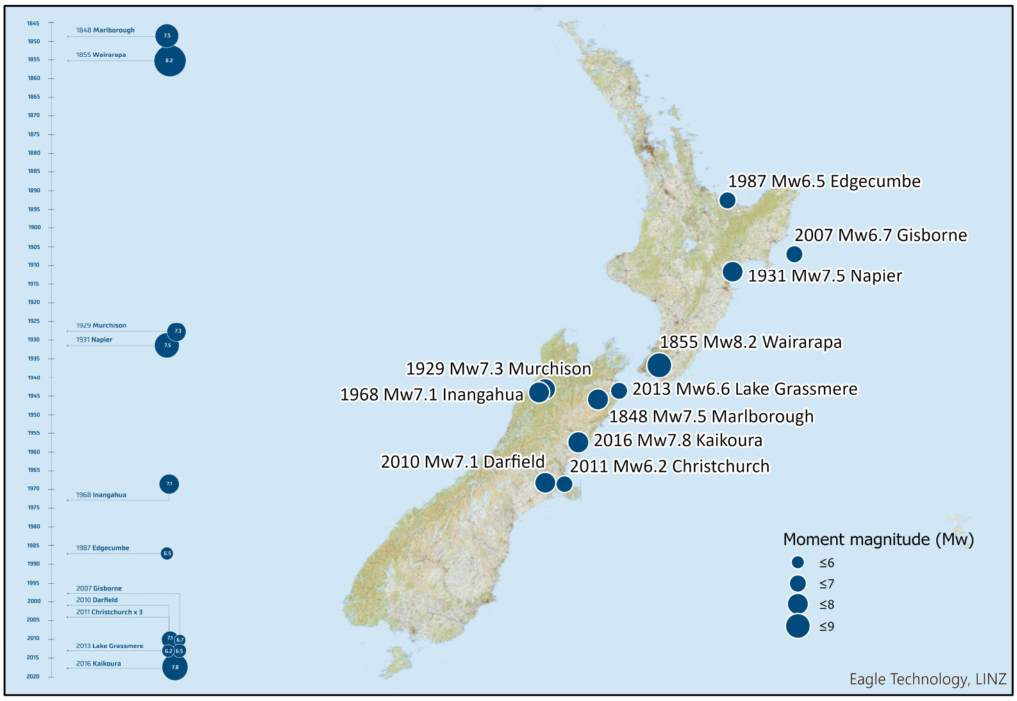

Figure 1: Distribution of earthquakes since European settlement within New Zealand for which liquefaction has previously triggered been reported.

Reports of liquefaction collated by Fairless and Berrill (1984), and mapped extents for events post-1984, provide a general overview of the distributions of liquefaction manifestations following historical earthquakes. Online geospatial software provides a platform where previous records of liquefaction can be presented, thus allowing for quick interrogation of areas that have previously liquefied. As part of this study, historical records of liquefaction have been collated and mapped into an online ArcGIS-based database that is publicly available on the QuakeCoRE Wiki Page at https://wiki.canterbury.ac.nz/display/QuakeCore/FP2%3A+Liquefaction+Impacts+on+Land+and+Infrastructure. The collated observations provide insights into the settings and soil types that have previously liquefied, while estimation of the shaking intensities of the causative events enables liquefaction triggering analyses to be calibrated against the actual observations.

2 METHODOLOGY

2.1 Collating historical records

Records of liquefaction were collated from Fairless and Berrill (1984) along with post-event publications and technical reports following more recent events (i.e. QuakeCoRE-GEER (2017)). Distributions of liquefaction in Whakatane following the 1987 Edgecumbe earthquake and in Napier following the 1931 Hawkes Bay earthquake were assessed by Masters students who examined post-event photographs and archives held within museums (see Mellsop (2017) and Elkortbawi (2017)). Records of liquefaction were subsequently digitised using simplified geometries into an online GIS-based dataset. Each record was given a separate datapoint outlining the affected area. Records were subsequently tagged with the reference, earthquake event, and type of observation (i.e. water ejection or lateral spreading). The inferred severity of liquefaction was assigned based on the land damage classification of None, Minor, Moderate, Major or Severe, generally following the definitions outlined by MBIE (2017). The level of confidence in the location and that the observation relates to liquefaction were additionally documented for each point. Locations where liquefaction was well documented have low levels of uncertainty whereas reports loosely tied to a person's property or region have a higher level of uncertainty.

3 COLLATED LIQUEFACTION OBSERVATIONS

Records of liquefaction currently included in the historical liquefaction database are shown in Figure 2 and are summarised in Table 1. The database will continue to be updated as new reports of liquefaction are identified, along with distributions of liquefaction in future events. It is important to note that non-observations do not necessitate a lack of liquefaction triggering. Liquefaction manifestations may have gone unreported in areas that were not visited during post-event reconnaissance, particularly for historical events.

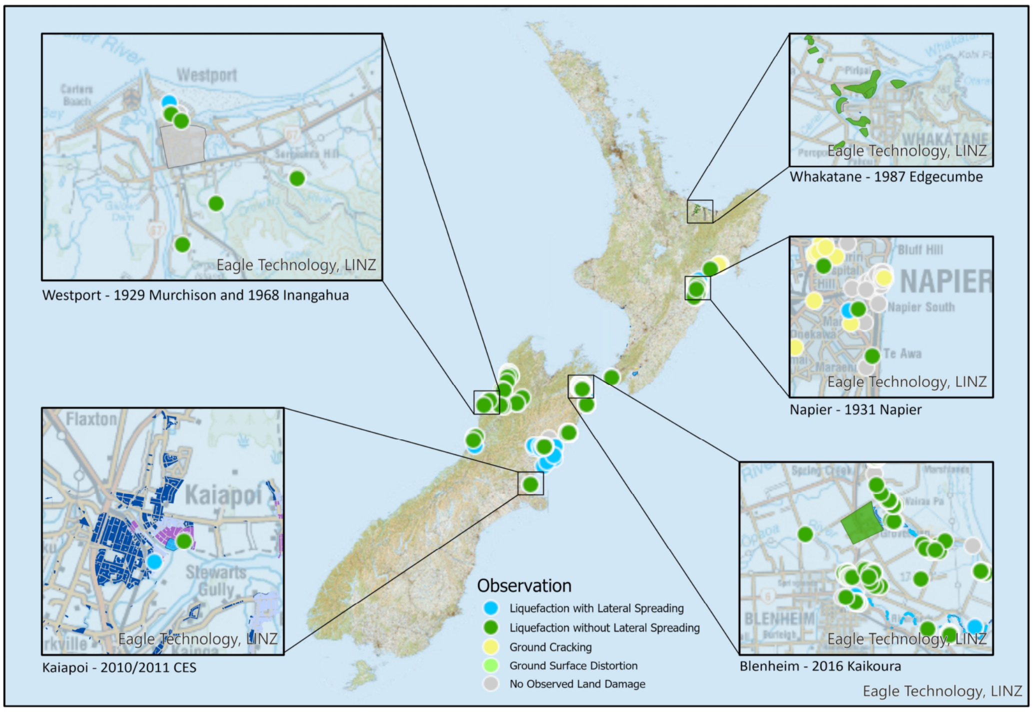

Figure 2: Spatial distribution of previous reports of liquefaction that are included in the online database.

Table 1: Summary of events included in the historical liquefaction database

Event	Report
1848 Marlborough Mw ~7.4-7.5	• Subsidence, sand craters releasing ground water observed along the lower Wairau River in Blenheim. • Localized liquefaction additionally reported along the west coast of the North Island as far north as Wanganui however no specific locations are listed.
1855 Wairarapa Mw ~8.1	• Expulsion of sand and water along the lower Wairau River near Blenheim. • Sand cones, fissuring of ground surface, and subsidence reported in downtown Wellington, Lower Hutt, Wairarapa, Manawatu Plains, and Ohau. Specific localities not provided.
1901 Cheviot Mw ~7.0	• Liquefaction and lateral spreading reported at properties in Sewell Street adjacent to the Kaiapoi River in Kaiapoi. • Localised liquefaction likely across the wider region based on observed damage but specific records not located.
1929 Murchison M7.3	• Liquefaction observed across the wider Westport, Karamea, Inangahua, and Greymouth areas. • Evidence of liquefaction and lateral spreading well documented proximal to mouth of the Karamea River and on river flats near Inangahua.

1931 Napier **M ~7.4-7.8**	• Localised liquefaction reported adjacent to waterways and coastal areas within Napier and towards Hastings. • Cases of no liquefaction inferred from historical photographs in central Napier.
1968 Inangahua **Mw 7.1**	• Liquefaction reported near rivers and estuarine settings near river mouths in the Inangahua, Westport, and Karamea areas; minor liquefaction reported in Greymouth. • Many of the sites that liquefied in the 1929 Murchison earthquake re-liquefied.
1987 Edgecumbe **Mw 6.5**	• Liquefaction mapped in recent fluvial deposits on the Rangitaiki Plains near the Rangitaiki and Tarawera Rivers. • Liquefaction and lateral spreading observed in recent fluvial deposits adjacent to the Whakatane River in Whakatane.
2010 – 2011 Canterbury Earthquake Sequence	• Widespread severe liquefaction and lateral spreading observed in eastern Christchurch. Worst hit areas (red zone) primarily adjacent to meandering rivers and the Avon-Heathcote Estuary to the east of the central city. Distributions of liquefaction proximal to rivers primarily correspond with areas of point-bar and paleo-channel deposition.
2013 Lake Grassmere **Mw 6.6**	• Localised liquefaction ejecta and lateral spreading mapped in recent fluvial and estuarine deposits adjacent to the Opawa River and Big Lagoon. • Minor liquefaction in reclamation fill near Wellington Harbour
2016 Kaikoura **Mw 7.8**	• Localized liquefaction mapped on alluvial plains proximal to rivers in the wider Waiau, Cheviot, Kaikoura, Ward regions. • Localised severe liquefaction observed in reclamation fill near Wellington waterfront. • Localised severe liquefaction and lateral spreading observed proximal to rivers to the east in Blenheim. Distribution confined to relatively low-elevation areas primarily corresponding with point-bar and paleo-channel deposits.

4 GEOMORPHIC SETTINGS OF LIQUEFACTION OBSERVATIONS

The spatial distributions of liquefaction reported following recent and historical events indicates that liquefaction has primarily occurred proximal to waterways in areas containing recent (Quaternary) fluvial deposits, while localised reports have been made in areas underlain by recent estuarine deposits. The geospatial dataset enables interrogation of commonalities in the spatial distributions, extents, and severities of liquefaction for different events. Initial comparison of the spatial location of the recorded observations with the ‘NZ River Centrelines’ dataset available from LINZ indicates that 80 percent of the reports are within 500 m of waterways (Figure 3).

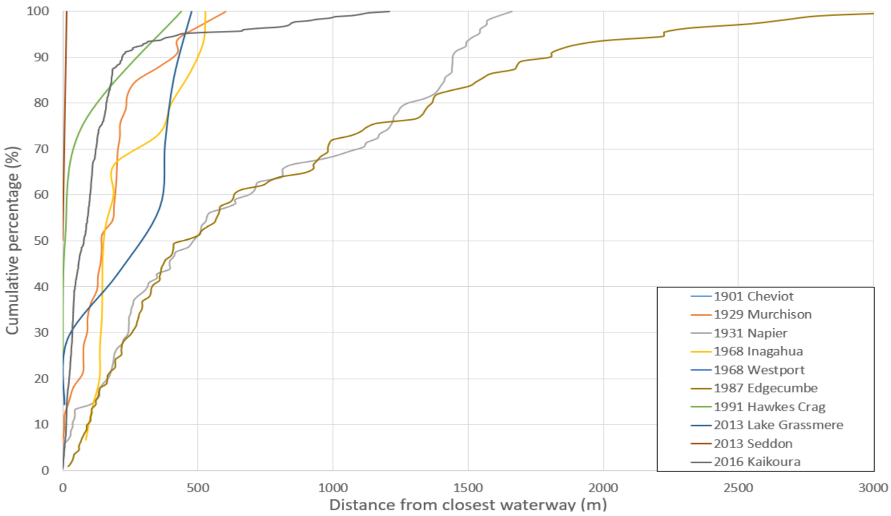

Figure 3: Cumulative percentage plot showing the distance of each reported liquefaction observation from the most proximal waterway for each historical earthquake included in the database.

Historical cases of liquefaction may also be paired with geotechnical data from the New Zealand Geotechnical Database (NZGD) to examine subsurface soil properties in areas of liquefaction and no liquefaction. It is important to note that areas where no liquefaction has been reported should not be treated as not liquefying unless this has been confirmed by a post-event site visit.

The mapped distribution of liquefaction in Blenheim following the 2016 Kaikoura earthquake indicated that liquefaction was confined to low elevation areas proximal to rivers and streams to the north and east of the township (Figure 4; see Bastin et al., 2018). Collated CPT from sites of known liquefaction indicate that the subsurface soils generally comprise a silt-to-clay cap underlain by thick layers of low relative density sands to silts (Figure 4). CPT traces in areas of no observed liquefaction generally indicate that the underlying soils comprise higher density deposits sands and silts. The q_c and I_c traces of these deposits additionally show higher variability, possibly due to inter-layering of soil types (Figure 4). Comparisons from Blenheim suggest that liquefaction hazard assessments should include consideration of depositional setting, in addition to the depth to groundwater and proximity to waterways. Recorded PGA during the Kaikoura earthquake was ~0.22 g; it is likely that liquefaction would be more widespread under a higher intensity event.

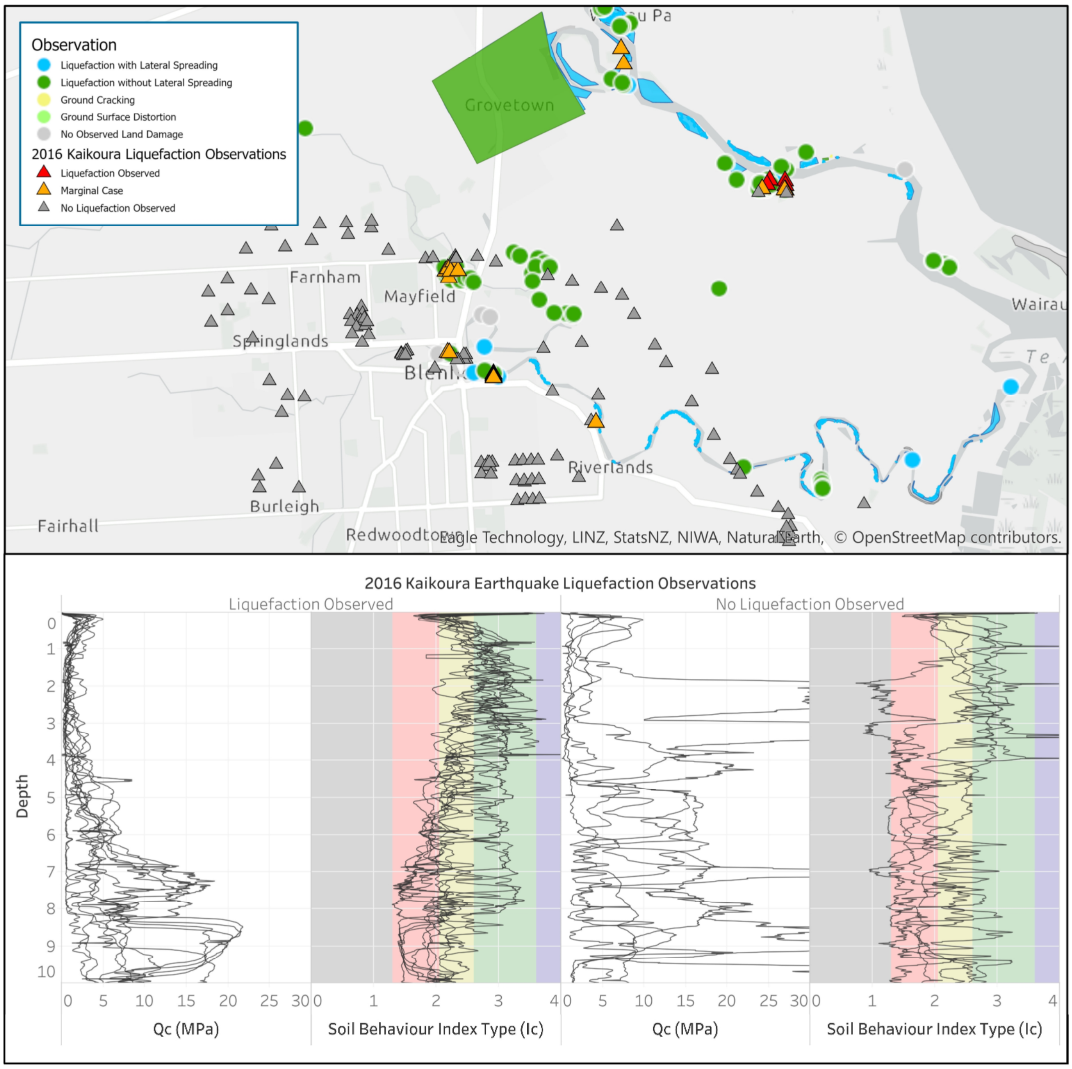

Figure 4: Mapped distribution of liquefaction and no liquefaction sites in Blenheim following the 2016 Kaikoura earthquake shown with collated CPT.

5 CASE STUDY COMPARISON OF OBSERVED AND PREDICTED LIQUEFACTION

Collated reports of liquefaction in Whakatane following the 1987 Edgecumbe earthquake show that localized liquefaction occurred proximal to the Whakatane River under an estimated PGA of ~0.15 g (Figure 5; Christensen, 1995). Recent liquefaction hazard maps developed for Whakatane using current state of practice methodologies suggest that the liquefaction hazard is high for much of the township. Comparison of the observed extent of liquefaction with that predicted from simplified analysis of existing geotechnical datasets using back-calculated PGA and depth to ground water models shows areas of inconsistent prediction (Figure 5; see Bastin et al., 2020 for discussion on analysis methodologies).

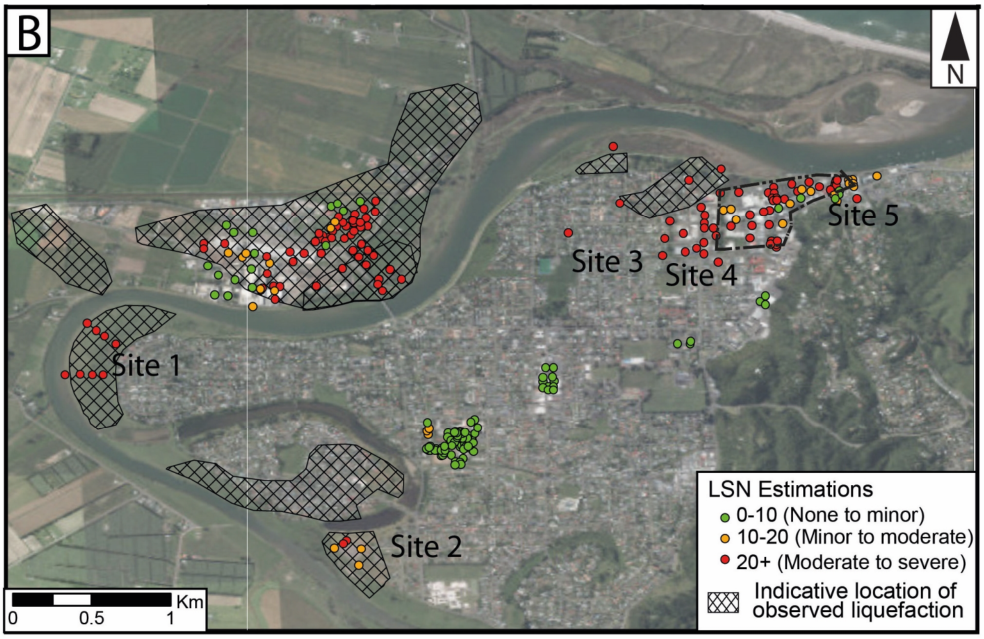

Figure 5: Comparison of observed and predicted extents of liquefaction in Whakatane for the 1987 Edgecumbe earthquake (modified from Bastin et al. 2020).

Geomorphic mapping indicates that the observed distribution of liquefaction corresponds with areas underlain by fluvial deposits comprising point-bar and paleo-channel deposits. Areas of inconsistent prediction are generally distal to the Whakatane River (Sites 4-5 in Figure 5). Potential reasoning for the variability in observed and predicted liquefaction includes differences in the age of the deposits, thin-scale inter-layering within the distal flood-plain, and/or the presence of pumice (see Bastin et al., 2020 for detailed discussion). The results highlight the importance of incorporating historical observations and geomorphic mapping as a form of ground truthing the assignment of liquefaction hazards.

6 POTENTIAL INCORPORATION IN LIQUEFACTION HAZARD MAPPING

The historical liquefaction database identifies areas that have historically exhibited surface manifestations of liquefaction for a given earthquake event and PGA. Areas where the earthquake-induced damage was well reported and/or photographed, and in which no liquefaction was reported, may be inferred as not exhibiting surface manifestations of liquefaction for the given earthquake PGA. Actual observations of liquefaction may subsequently be used to calibrate predicted liquefaction severities if simplified liquefaction triggering analyses are conducted using estimated shaking intensities of the causative earthquake event. The collated dataset therefore provides a valuable tool kit to verify and/or cross-examine the interpreted liquefaction hazard from simplified analyses.

The collated reports indicate that liquefaction has primarily been observed in relatively low elevation areas proximal to waterways that are underlain by recent fluvial deposits. The consistency in the geomorphic settings of the reported observations suggests that these settings contain deposits with low resistance to liquefaction-triggering. Geomorphic mapping may therefore be used as a 'first-pass' filter to identify areas likely to contain deposits susceptible to liquefaction as part of the Level A (Desktop) and Level B (Calibrated Desktop) studies. It is recommended that this be done in conjunction with published geology and consultation with shallow groundwater records.

7 CONCLUSIONS

Historical records indicate that consequential liquefaction has occurred during upwards of 11 earthquakes in New Zealand since European settlement and prior to the 2010 Darfield earthquake. The historical records have been collated and geospatially plotted into an online, open-access ArcGIS database.

The collated historical records of liquefaction provide an independent methodology by which liquefaction hazard assessments may be 'cross-checked' and/or supplemented in the absence of geotechnical investigations. It is anticipated that the database will assist Level 'A' and 'B' liquefaction hazard assessments across the country.

The spatial distributions of liquefaction indicate that liquefaction primarily occurs in low elevation areas proximal to waterways. Geomorphic mapping indicates that liquefaction manifestations in Whakatane following the 1987 Edgecumbe earthquake and in Blenheim following the 2016 Kaikoura earthquake occurred within recent point-bar and paleo-channel deposits. Subsurface deposits in these areas generally contain thick layers of low relative density sands to silts.

Predicted liquefaction hazards may be calibrated using actual observations of liquefaction recorded for a given earthquake event and associated PGA. Comparisons of observed and predicted liquefaction in parts of New Zealand have found that the simplified liquefaction triggering analyses over-predict liquefaction hazards in certain soil types, including inter-layered soils and those containing pumice. The collated historical liquefaction dataset subsequently provides a valuable tool kit that may be used to verify and/or cross-examine the liquefaction hazard interpreted from simplified analyses.

8 ACKNOWLEDGEMENTS

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