Cross-Checking Liquefaction Hazard Assessments with Liquefaction Observations from New Zealand Earthquakes and Paleo-liquefaction Trenching

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ABSTRACT

Liquefaction has been reported following upwards of 13 recent and historical earthquakes in New Zealand. Collating reports outlining the extents of liquefaction manifestation following these events provides insights into the distributions of sediments with low cyclic resistances to liquefaction, and enables liquefaction hazard assessments to be cross-examined. Collated reports following the 1987 Edgecumbe earthquake indicate that localized liquefaction manifestations occurred proximal to the Whakatane River in Whakatane. However, analysis of an extensive geotechnical dataset using back-calculated peak ground accelerations and depth to ground water models show that the simplified methodologies predict widespread and severe liquefaction for much of Whakatane. Comparison of observed and predicted manifestations with local geomorphic variability indicates areas of inconsistent prediction occur within the distal flood-plain, while manifestations are accurately predicted within point-bar and paleo-channel deposits. Paleo-liquefaction trenching confirms an absence of liquefaction features in areas where liquefaction was predicted yet not observed, and provides a methodology by which predicted liquefaction extents can be moderated. This paper highlights the potential applications of incorporating historical extents of liquefaction manifestation, with geomorphic mapping, and paleo-liquefaction trenching into liquefaction hazard assessments.

1 INTRODUCTION

Liquefaction and associated lateral spreading poses a significant hazard to the built environment, as highlighted following the 2010-2011 Canterbury Earthquake Sequence (CES), and 2016 Kaikoura earthquake (Quigley, 2017; GEER, 2017). Liquefaction during the CES heightened awareness of the consequences of liquefaction to the built environment and associated financial losses. As a result, revisions to the Resource Management Act (1991) have been proposed which will require councils to better understand natural hazards in their area, including producing relevant hazard maps as part of their planning requirements. Liquefaction hazard maps are typically derived from the identification of low lying Quaternary aged alluvial deposits from geological maps, then further refined using simplified CPT- and SPT-based liquefaction triggering procedures on available geotechnical data. Historical cases of liquefaction are often not considered in the development of these maps, nor are the resultant maps cross-checked with observed performances from historical earthquakes.

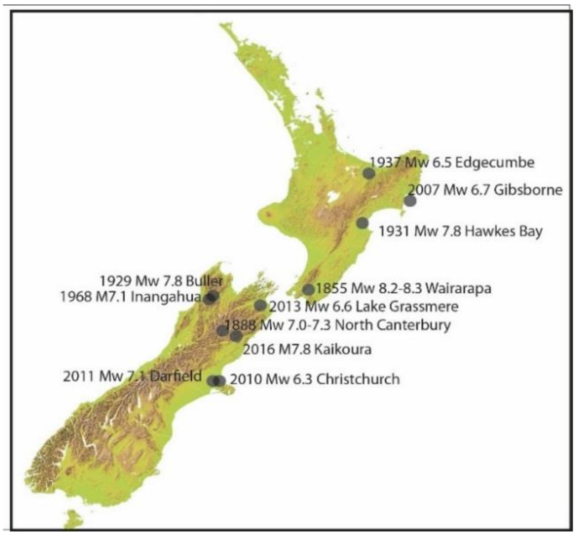

Figure 1: Historical earthquakes known to have triggered liquefaction in New Zealand.

Historical records indicate that upwards of 13 earthquakes have triggered liquefaction within parts of New Zealand prior to the CES, resulting in damage to the built environment (indicated in Figure 1; e.g. Fairless and Berrill, 1984). Much of the post-event literature indicates that localized liquefaction occurred proximal to waterways during these events, however recent liquefaction hazard assessments suggests that soils with low cyclic resistances to liquefaction are widespread throughout the urban centres in New Zealand. Recent studies following the 2010-2011 Canterbury earthquake sequence (CES) have shown inconsistencies between the predicted and observed extents of liquefaction manifestation (i.e. van Ballegooy, 2016). Many of the areas of over-prediction have been shown to correspond with silty back-swamps distal the rivers within the region (Beyzaei et al., 2017). The potential over-prediction of liquefaction hazards may result in unnecessary restrictions on land development and retrofitting of existing infrastructure, and may direct efforts away from areas that are truly susceptible to liquefaction.

Records of ‘ground cracking’ and ‘quick sand’ are present throughout local newspaper articles, and archives following large earthquakes in New Zealand, while maps outlining liquefaction manifestations are scattered throughout publications and technical reports following more recent events (e.g. Figures 2 & 3). Collation of the historical records enables extents of liquefaction manifestation to be approximated, and thus the distribution of sediments susceptible to liquefaction during future events to be determined. The New Zealand geotechnical database (NZGD) enables liquefaction analyses to be conducted on a regional basis. The extents of liquefaction manifestation predicted by the simplified liquefaction methodologies for a given earthquake shaking intensity may therefore be predicted for a given region. Comparison of predicted extents of liquefaction manifestation, with that observed from historical earthquakes, provides an independent methodology by which liquefaction hazard assessments may be validated. In addition, comparison of predicted and observed extents of liquefaction with geomorphic maps provides insights into areas where liquefaction typically manifests, and areas where over-prediction tends to occur. The presence and/or absence of liquefaction features may additionally be cross-examined through paleo-liquefaction trenching investigations.

This paper presents an overview of the potential applications of using historical observations of liquefaction manifestation, geomorphic mapping, and trenching in assessing liquefaction hazards using examples from Whakatane following the 1987 Edgecumbe earthquake.

"Fissures opened parallel with the water front for chains back; the wharf warped slightly; the railway-lines twisted; and the long straight of the break-water mole showed gentle swings from side to side and up and down as the embankment settled unevenly on the uncompacted estuarine deposits".

Figure 2: Example of a historical record referring to the occurrence of liquefaction following the 1929 Murchison earthquake (Collated from Carr (2004)).

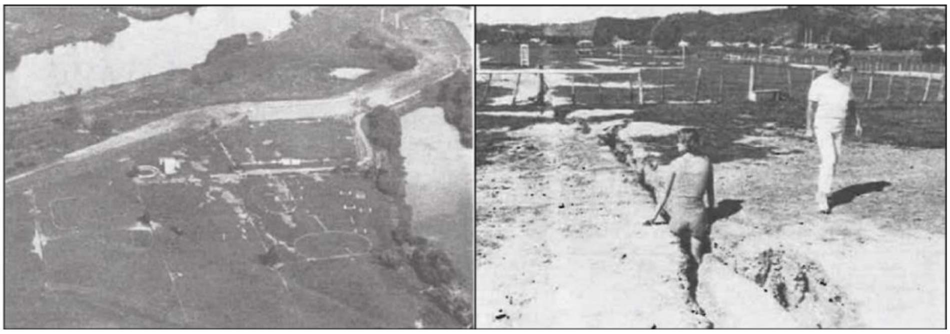

Figure 3: Historical photographs outlining the occurrence of liquefaction in Whakatane following the 1987 Edgecumbe earthquake (Collated from Christensen (1995)).

2 COLLATING HISTORICAL ACCOUNTS OF LIQUEFACTION

Reports of earthquake-induced damage to land, infrastructure, and contents are present in letters, photographs, and diaries held within local archives across New Zealand. In some cases the reports are scattered with references to 'boils', 'fissuring', 'flooding' and other features indicating the occurrence of liquefaction (Figure 2). The presence or absence of ejecta, cracking, and/or flooding in post-event photography and reports provides key liquefaction and non-liquefaction case history sites (e.g. Figure 3). The resultant manifestations may be inferred across the surrounding geomorphological setting to provide a more comprehensive overview of the likely liquefaction manifestations. For more recent earthquakes, such as the 1987 Edgecumbe earthquake, reports of liquefaction manifestation are present in post-event publications and technical reports, and may be supplemented by local residents who are often able to recall specific localities. Combining all available resources enables the extents of liquefaction manifestations to be constrained for recent and historical events in New Zealand. Work to collate observational records into an online GIS-based database are ongoing and will result in a published dataset outlining liquefaction and non-liquefaction case history sites.

Collation of technical reports, journal papers, and historical photographs, along with local residents observations indicates that localized ejecta and lateral spreading occurred proximal to the Whakatane River in Whakatane following the 1987 Edgecumbe earthquake (indicated in Figure 4; i.e. Pender and Robertson, 1987; Christensen, 1995). No manifestation was observed within the Central Business District (CBD) nor in the suburbs distal to the river (Figure 4).

3 COMPARISON OF OBSERVED AND PREDICTED LIQUEFACTION MANIFESTATION

Collated liquefaction and non-liquefaction case history sites provides a means by which the results of the simplified liquefaction triggering procedures and associated liquefaction hazard assessments may be cross-checked. The extents of liquefaction manifestation predicted for a given earthquake may be back-calculated using event-specific peak ground accelerations and depth to groundwater models. The results may be compared with that observed to identify areas of consistent and inconsistent prediction. As peak ground accelerations and depth to groundwater data are not typically available for historical events, these values must be estimated. The methodology used to derive peak ground acceleration (PGA) and depth to groundwater models for Whakatane at the time of the Edgecumbe earthquake is summarized in Mellsop et al. (2017; these proceedings), and Bastin et al. (2017).

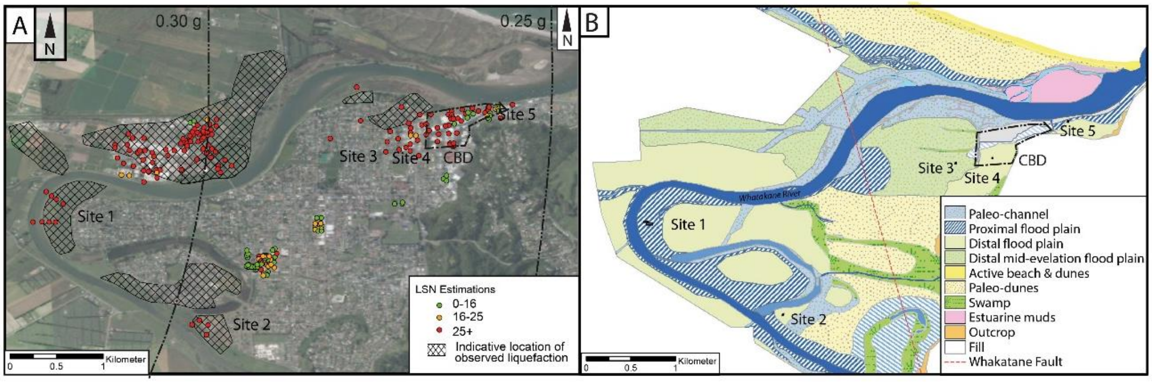

Figure 4: A) LSN predicted from simplified analyses using median peak ground acceleration and depth to ground water models and plotted with median PGA (dotted lines) and recorded extents of liquefaction (hatched areas). B) Geomorphic map with the location of trenches indicated.

Work undertaken using median modelled PGA and depth to groundwater derived for the Edgecumbe earthquake indicates that widespread and severe liquefaction (LSN 25+) is predicted for much of Whakatane (Figure 4; see Mellsop et al. (2017) for a detailed discussion). The LSN is shown to over-predict the severity of liquefaction manifestation within the Central Business District (CBD) compared to that inferred from the historical reports (Figure 4). Sensitivity analysis undertaken using lower-bound estimated PGA and depth to groundwater model additionally over-predicted the occurrence of liquefaction manifestation in the CBD however, under-predicted the severity of liquefaction at sites where liquefaction was well documented. The manifestations predicted using the median PGA and depth to groundwater models are therefore considered to best fit the post-event observational record of liquefaction.

4 COMPARISON OF OBSERVED LIQUEFACTION WITH GEOMORPHOLOGY

Geomorphic mapping provides insights into the settings where liquefaction was predicted and manifested and settings where liquefaction was predicted by the simplified liquefaction triggering methodologies yet was not observed. Geomorphic maps may be produced from analysis of topographic variability across an area, coupled with basic river morphologies, positions of historical river channels, and a review of available literature. The resultant observations provide insights into the paleo-depositional settings and likely subsurface sediment types within an area.

Geomorphic maps of Whakatane indicate that the township is primarily situated upon the low-elevation (0 to 3 m above sea level (a.s.l)) flood plain of the meandering Whakatane River. The area is locally truncated by higher elevation (2 to 10 m a.s.l) paleo-beach ridges associated with shoreline regression and coastline progression following the ~6,500 year before present highstand. The area is underlain by alluvial sands, silts, and granules deposited by the Whakatane River, and near-shore marine sands and silts associated with coastal regression (Figs. 1 & 2; Nairn and Beanland, 1989). Shoreline progradation of up to 10 km is inferred following the Whakatane (1850 y BP) and Kaharoa (800 y BP) pyroclastic eruptions in the Taupo Volcanic Zone (TVZ). In addition, up to 1.5 m of sediment accumulation is inferred within the active flood-plain of the Whakatane River following the 1886 Tarawera eruption (Christensen, 1995). Paleo-channels and ox-bow lakes associated with cut-off meander bends of the Whakatane River are present to the south-west and west of the township and recognizable as topographic depressions and swamp-land (Figure 4; Christensen, 1995). Tidal mud flats present near the mouth of the Whakatane River were infilled with rock tailings in the early 1900’s as part of reclamation for development of the CBD (Figure 4B) (WDC archives). Swamps within the distal flood-plain were additionally infilled during the development of the township.

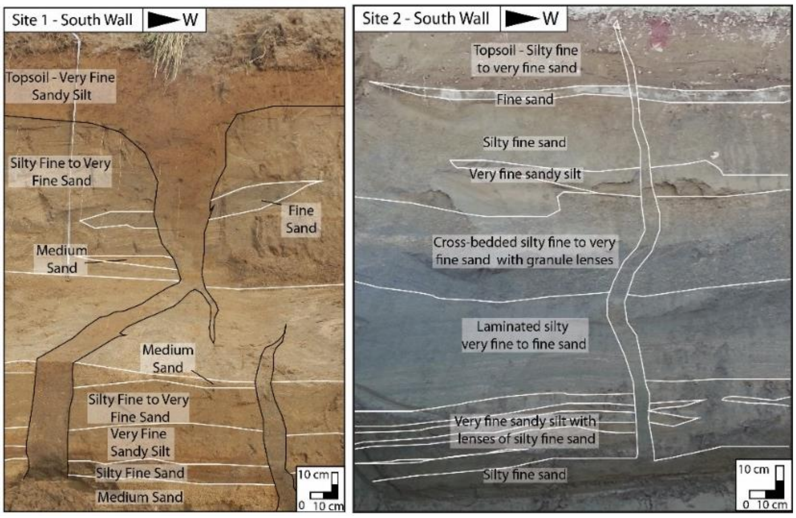

Figure 5: Interpreted field photographs of liquefaction features formed during the Edgecumbe earthquake as observed at Sites 1 and during trenching.

Areas of reported liquefaction manifestation following the Edgecumbe earthquake are shown to correspond with the inside banks of meander bends and paleo-channels of the Whakatane River (Figure 4B). These areas are likely underlain by thick successions of recent, fluvial deposited, and loosely consolidated fine to medium sands and granules, including sediments deposited following the Tarawera eruption. In contrast, no liquefaction manifested in the areas distal to the river which comprise paleo-dunes and the distal flood-plain (Figure 4). Sedimentation within the distal flood-plain is limited to large bank-overtopping flood events and thus the area generally comprises thinly inter-layered over-bank deposits of silts and fine sands. As a result, the near surface (>10 m) sediments are likely to be comparably older (>500 y BP) than those deposited proximal to the active river channel.

5 GROUND TRUTHING LIQUEFACTION EXTENTS THROUGH TRENCHING

Inconsistencies between the predicted and observed extents of liquefaction manifestation within Whakatane highlights potential shortcomings of the simplified liquefaction triggering methodologies and associated manifestation severity parameters. These inconsistencies have significant implications for liquefaction hazard assessments in the region, and across similar geologic settings in New Zealand. Paleo-liquefaction trenching provides an alternative methodology by which the occurrence or non-occurrence of liquefaction may be examined, and the associated liquefaction hazard may be cross-checked.

Paleo-liquefaction trenching in Whakatane enabled the observed and predicted extents of liquefaction to be ‘ground-truthed’ and the presence of pre-Edgecumbe liquefaction features to be examined. Trenching was conducted at sites where liquefaction was predicted by the simplified methodologies and was observed (Sites 1 and 2), and sites where liquefaction was predicted by the simplified methodologies yet was not observed (Sites 3 - 5). Trenches were orientated perpendicular to the closest bank of the Whakatane River which gave the best chance of intersecting lateral spreading features, and were excavated to maximum lengths possible at the selected sites (indicated in Figure 4).

Trenching at sites within the low-elevation flood-plain of the Whakatane River which are known to have liquefied during the Edgecumbe earthquake (Sites 1 and 2), revealed approximately 20 to 40 cm wide lateral spreading fissures that cross-cut the fluvial stratigraphy. The features generally increase in width with depth indicating that they formed by the upwards ejection of liquefied sediment (Figure 5). The margins of the features exhibited limited re-working (i.e. bioturbation of contacts) indicating that they most likely formed during the Edgecumbe earthquake. No

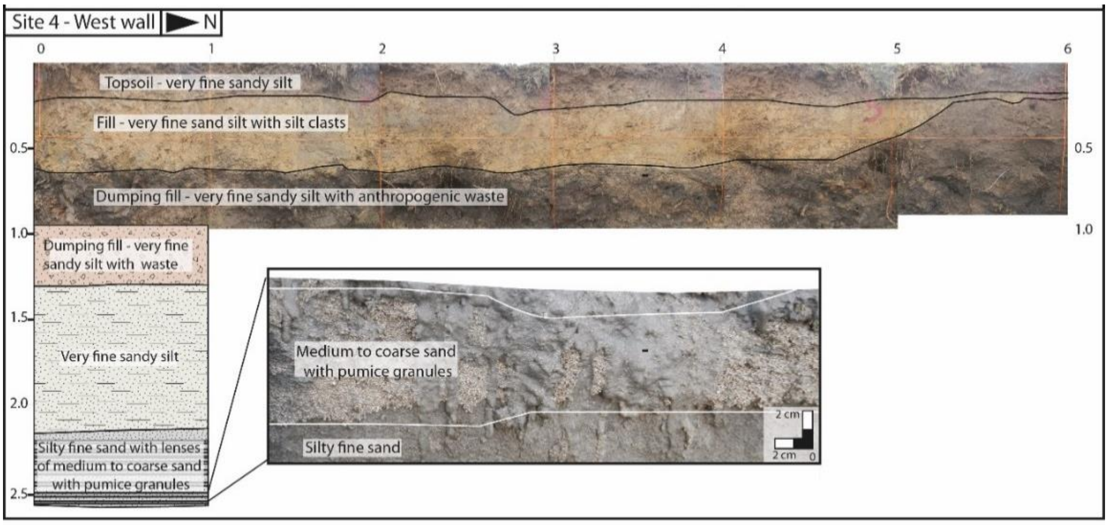

Figure 6: Interpreted photo log of the trench at Site 4 where liquefaction was predicted for the Edgecumbe earthquake by the simplified methodologies yet was not observed.

evidence for pre-1987 liquefaction was observed in the trenches, indicating that the sediments had most likely not liquefied since their deposition and prior to the Edgecumbe earthquake. The exposed stratigraphy comprises laminated silty fine sand and fine sandy silt with lenses of fine sand that are cross-cut by channelized lenses of cross-bedded medium sand with granules of pumice. The stratigraphy is interpreted to represent recent fluvial deposits of the Whakatane River associated with its avulsion to its present location and associated point-bar deposits. The upper 1.5 m of sediment likely reflects active deposition following the 1886 Tarawera eruption.

In comparison, no liquefaction features were observed during trenching at sites where liquefaction was predicted by the simplified methodologies yet was not observed (Sites 3-5). The absence of liquefaction features further confirms that liquefaction did not manifest at these sites during the Edgecumbe earthquake (Figure 6). The exposed stratigraphy comprises anthropogenic fill associated with development of the township, and is underlain by silts with inter-layered lenses of fine sand and medium to coarse sand with granules of pumice (Figure 6). The stratigraphy is generally consistent with the positions of the sites in the distal flood-plain of the Whakatane River, and are interpreted as over-bank flood deposits. It is considered unlikely that significant sediment accumulation occurred at these sites following the 1886 Tarawera eruption.

Potential reasoning for the inconsistencies between the predicted and observed manifestations of liquefaction are the subject of ongoing research. One of the more noticeable variations between the sites is the inferred variability in soil ages between Sites 1-2, and Sites 3-5, which has been shown to influence liquefaction potential (e.g. Hayati et.al. (2008)). Additional factors potentially influencing liquefaction triggering at the site include variability in measured and actual ground-water depths, the inability of the CPT to distinguish thin inter-layering of sands and silts in distal back-swamps, which has been shown to minimize liquefaction triggering (Beyzaei et al., 2017), and the presence of pumice granules for which the simplified methodologies are not developed (Orense et al. 2012).

6 POTENTIAL APPLICATIONS TO LIQUEFACTION HAZARD ASSESSMENTS

Collated reports indicate that liquefaction manifestation occurred within recent paleo-channel and point-bar deposits in Whakatane during the 1987 Edgecumbe earthquake which comprise loose and unconsolidated fine sand with lenses of silt, and medium to coarse sand with pumice granules. The upper 1.5 m of the soil profile is considered likely to have been deposited in the last 150 years (i.e. post Tarawera), and the under-lying strata is likely geologically young. No manifestations were observed within the distal flood plain of the Whakatane River, despite the simplified methodologies predicting widespread and severe liquefaction manifestations. Trenching indicates these areas are underlain by silts with inter-layered lenses of fine sand and medium to coarse sand with granules of pumice which are interpreted to be comparably older (>150 years) than those exposed at Sites 1 and 2. Similar spatial trends in liquefaction manifestations are indicated in post-event literature following other recent and historical earthquakes within New Zealand. Descriptions often indicate that fissuring and sand-boils formed in areas proximal to waterways (i.e. Figure 2), while no records of liquefaction manifestation are generally reported to the rivers.

The recorded extents of liquefaction manifestation indicates that young, unconsolidated point-bar and paleo-channel deposits are highly susceptible to liquefaction, and thus are likely to liquefy during future events. The extents of liquefaction manifestations during future events generating similar PGA are considered likely to be similar to that of previous events. However, no inferences can be made for events generating higher PGA. The historical extents may therefore be used to approximate liquefaction hazards for future events generating similar ground accelerations. Geomorphic mapping may additionally be employed to identify areas potentially underlain by sediments with low cyclic resistances to liquefaction in areas where geotechnical testing data is lacking. The presence or absence of liquefaction features at given site may be 'ground-truthed' through paleo-liquefaction trenching. Combining historical extents of liquefaction, geomorphic mapping, and paleo-liquefaction trenching enables the assigned liquefaction hazard to be cross-examined for a given area, and provides a methodology by which predicted liquefaction extents can be moderated.

7 CONCLUSIONS

Liquefaction manifestations have been reported following upwards of thirteen recent and historical earthquakes in New Zealand. Collation of historical records outlining extents of liquefaction manifestation provide an independent methodology by which liquefaction hazard assessments may be 'cross-checked', and key liquefaction and non-liquefaction case history sites established. The extents of liquefaction manifestations predicted for a given earthquake may be derived from simplified analysis of existing geotechnical datasets using back-calculated PGA and depth to ground water models. Comparison of predicted manifestations with that observed, enables areas of consistent and inconsistent prediction to be identified. The presence or absence of liquefaction features in these areas may be confirmed through paleo-liquefaction trenching.

Collation of historical records of liquefaction manifestation within Whakatane following the 1987 Edgecumbe earthquake indicates that liquefaction occurred proximal to the Whakatane River. Comparison of the collated extents of liquefaction manifestation with that predicted from the simplified methodologies using back-calculated PGA and depth to ground water models indicates areas of inconsistent prediction occur distal to the Whakatane River. Geomorphic mapping indicates that liquefaction manifestations occurred with recent point-bar and paleo-channel deposits. Trenching confirms the presence of liquefaction features in areas where it was reported, and an absence of features in areas where liquefaction was predicted yet not observed. Potential reasoning for the inconsistent predictions include variability in the depositional setting, age of the deposits, thin-scale inter-layering present within the distal flood-plain, and/or the presence of pumice. The results highlight the potential applications of incorporating historical extents of liquefaction, geomorphic mapping, and paleo-liquefaction trenching into the development of liquefaction hazard assessments.

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