13th Australia New Zealand Conference on Geomechanics – Acosta-Martínez & Lehane (Eds.)
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Insights into the liquefaction hazard in Napier and Hastings based on the assessment of data from the 1931 Hawke's Bay, New Zealand, earthquake

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ABSTRACT: Hawke's Bay is situated on the east coast of the North Island of New Zealand and has experienced several earthquakes in the past during which triggered liquefaction. The 1931 Hawke's Bay earthquake is particularly interesting because it was one of the most damaging earthquakes and the deadliest earthquake in New Zealand's history. This study provides insights into the actual versus predicted liquefaction hazard in Napier and Hastings. Towards this end, the simplified Cone Penetration Test (CPT)-based liquefaction triggering evaluation procedure proposed by Boulanger & Idriss (2014) (BI14) is used in conjunction with Liquefaction Severity Number (LSN) framework to predict severity of surficial liquefaction manifestations across the region for the 1931 M_S7.8 Hawke's Bay event. A comparison of the results with post-event observations suggests that the liquefaction hazard is being over-predicted. One possible cause for this over-prediction includes the shortcomings liquefaction damage potential frameworks to predict the severity of surficial liquefaction manifestations in silty soil deposits. This study demonstrates how historical earthquake accounts in a region can be used to assess the risk of the region from future earthquakes.

1 INTRODUCTION

The objective of the study presented herein is to provide insights into the actual versus predicted liquefaction hazard of Hawke's Bay (i.e. Napier and Hastings), New Zealand. The Hawke's Bay region is one of the most seismically active regions in New Zealand, with the largest historical earthquake being the 3 February 1931, surface-wave magnitude (M_S) 7.8 Hawke's Bay earthquake. The 1931 event, also known as Napier earthquake, was the deadliest and one of the most damaging earthquakes in New Zealand's history. Damage from the earthquake occurred over an ~200 km stretch from Gisborne in the north to Waipukurau in the south.

The Tukituki, Tutaekuri, and Ngaruroro Rivers discharge into the sea in southern Hawke's Bay. Through time, these rivers transported eroded material from the mountains in the west and deposited them over an extensive alluvial plain, known as the Heretaunga Plains (Lee et al. 2011). The towns of Napier and Hastings are situated on these deposits near the southern part of the bay, with Napier on the coast and Hastings about 9.5 km inland.

The combination of the depositional environment of the soils in southern Hawke's Bay and high seismicity of the region potentially results in a high regional liquefaction hazard. Evidence of this is that liquefaction and lateral spreading were documented to have occurred in the region following the 1863 Southern Hawke's Bay earthquake, 1904 Cape Turnagain earthquake, 1921 Central Hawke's Bay earthquake, 1931 Hawke's Bay earthquake, and the 1932 Wairoa earthquake. Of interest to this study is the occurrence of liquefaction during the 1931 Hawke's Bay earthquake because the effects of the earthquake on land and buildings were relatively well-documented, which allows for a detailed study to be performed.

The severity of surficial liquefaction manifestations in Napier and Hastings is predicted for the 1931 Hawke's Bay earthquake scenario using the Cone Penetration Test (CPT)-based simplified liquefaction evaluation procedure proposed by Boulanger & Idriss (2014) (BI14) in conjunction with the Liquefaction Severity Number (LSN) (van Ballegooy et al. 2014) liquefaction damage potential framework. These predictions are then compared with historical accounts of liquefaction in Napier and Hastings. Insights are then drawn from this comparison about where current procedures can be expected to yield accurate predictions of the liquefaction hazard for future events and where the predictions are expected to be less certain.

2 BACKGROUND

2.1 *Tectonics*

Hawke’s Bay is located on the east coast of the North Island in a seismically active region where the Pacific Plate subducts under the Australian Plate. A deformed zone results from this convergence and manifests in extensive faulting with strike-slip, normal, and reverse displacement.

2.2 *Geology and geomorphology*

The Heretaunga Plains are part of the lowlands and were formed by the accumulation of eroded sediments and volcanic material transported by the Ngaruroro and Tutaekuri Rivers from the greywacke mountain ranges and the Taupo Volcanic Zone, respectively, as well as marine sediments deposited by the transgressing sea into the Heretaunga depression (Dravid & Brown 1997). A review of the regional geomorphology provides information about the sedimentary origin and relative age of the upper 1-5 m of sediments across the area, which provides insights, albeit qualitative, into the liquefaction susceptibility of the deposits (e.g. Youd & Hoose 1977). The dominant landforms in the developed areas are estuary plains, older (but still Holocene) fluvial landforms, and human modified ground (e.g. fill), which, per Youd & Hoose (1977), range in liquefaction susceptibility from moderate to high.

2.3 *The 1931 Hawke’s Bay earthquake*

The $M_S7.8$ Hawke’s Bay earthquake occurred on 3 February 1931 at 10:47 am New Zealand local time (Haines & Darby 1987; Dowrick & Smith 1990). The estimated moment magnitude, M_W, for the event varies from study to study but is generally in the range of $M_W7.4$-7.9. The epicenter of the main shock is estimated to be located 25 km NNE of Napier (Dowrick 1998): 39.3° S, 177.0° E. A large number of aftershocks followed the main shock, with 596 aftershocks occurring in February 1931 (Adams et al. 1933). Based on the recurring aftershocks, Adams et al. (1931) concluded that the focal depth of the main shock was ~15 to 20 km. The main shock was predominantly a thrust event generated by slippage on a reverse fault dipping steeply to the northwest under Hawke’s Bay. It was also accompanied by strike-slip movement.

Surface deformation from the Hawke’s Bay earthquake consisted of a zone of subsidence at Hastings (maximum of 1 m) and a zone of uplift northeast of Napier (maximum of 2.7 m). As a result of the surface deformation, the Ahuriri Lagoon was uplifted and consequently drained, allowing regions of the Ahuriri Lagoon to be reclaimed. The tectonic deformations also resulted in the Tutaekuri River, which prior to the earthquake flowed into the southern part of the lagoon, to change its course and bypass the lagoon to the south post-earthquake.

Based on the severity of the damage in different locations around Hawke’s Bay, Dorwick (1998) developed Modified Mercalli Intensity (MMI) isoseismal maps for the event. The effects of the earthquake shaking were greatest in the towns of Napier and Hastings (MMI X). The ground motions for the event were simulated by Bayless et al. (2017) using the Southern California Earthquake Center (SCEC) Broadband Strong Ground Motion Simulation Platform (BBP). A shallow crustal earthquake source model was used for the simulation, and the resulting peak ground acceleration (PGA) map is shown in Figure 1. The simulated PGAs were converted to MMI intensities using the Ground Motion Intensity Conversion Equation (GMICE) from Caprio et al. (2015) and compared with MMI isoseismal map from Dorwick (1998). The two sets of MMI isoseismal maps were in good agreement.

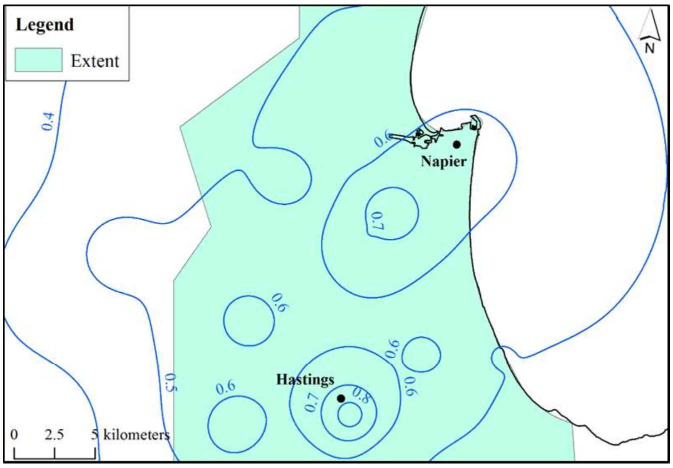

Figure 1. PGA (g) contour map for the 1931 Hawke’s Bay earthquake based on MMI.

In addition to the well-documented changes in elevation discussed above, faulting, liquefaction, and landslides during the 1931 event were also well documented (Callaghan 1933; Dowrick 1998; Hull 1990; Marshall 1933). Of specific interest to this study, the occurrence of liquefaction was documented in historical photographs (e.g. Figure 2), personal accounts, books, and newspaper clips. Additionally, published journal articles after the event provide scientific description of liquefaction, despite the phenomenon not being fully understood at the time.

Figure 2. Sand boil resulting from the 1931 Hawke's Bay earthquake *(from the archives of the MTG Hawke's Bay Museum)*.

3 LIQUEFACTION STUDY

To provide insights about the predicted versus actual liquefaction hazards in Napier and Hastings, the BI14 liquefaction triggering evaluation procedure is used in conjunction with LSN framework to predict severity of surficial liquefaction manifestations across the region for the 1931 event. The predictions are then compared with post-earthquake observations.

3.1 *Collection of 1931 liquefaction records*

Information on occurrences of liquefaction around Hawke's Bay was compiled by Brodie & Harris (1933), Callaghan (1933), Henderson (1933), Marshall (1933), Fairless & Berrill (1984), Dowrick (1998), and Dellow et al. (2003). Most notably, Callaghan (1933) reports observations of liquefaction manifestations following the earthquake, and Fairless & Berrill (1984) report liquefaction effects in Heretaunga Plains, Taradale, Clive, Esk Valley, Mohaka, Tangoio, Petane, and Gisborne. The reported manifestations included sand boils or mud spouts or sand geysers, cracks and fissures, differential settlement, and lateral spreading.

Also, a visual study was performed by the first author of photographs, newspaper clips, and personal accounts from 1931 from the archives of the MTG Hawke's Bay Museum & Art Gallery, Napier Public Library, and Hastings District Libraries, from published books on the history of Hawke's Bay, and from personal communications with the local historian Mr. Michael Fowler (Fowler, pers. comm.).

The quality and spatial distribution of the liquefaction observations are highly variable, partly due to the lack of understanding of the liquefaction phenomenon at the time and partly due to the low population density of the region in 1931. Post-earthquake observers did not explicitly search for liquefaction manifestations, and hence, historical cases of liquefaction had to be inferred from available information that is undoubtedly incomplete. Thus, it is highly probable that occurrences of liquefaction were not documented. More details on the liquefaction observations in Hawke's Bay and particularly in the study area are described by El Kortbawi (2017).

3.2 *Characterization of soil profiles*

Subsurface site investigation data in Hawke's Bay are available from the New Zealand Geotechnical Database (NZGD) and Tonkin and Taylor Geotechnical Database (TTGD). For this study, 897 CPT soundings were considered for use in the liquefaction study. However, 29 of the soundings were discarded because pre-drilling was performed to bypass buried utilities and extended into the liquefiable layers. Accordingly, the data obtained from these CPT (i.e., tip resistance, q_c, and sleeve friction, f_s) for this portion of the liquefiable layers are unreliable. The LSN framework nominally requires the CPT to be performed to the full depth of liquefiable soils, down to a maximum depth of 20 m. However, this criterion was relaxed to a maximum depth of 10 m, the same depth criterion used by van Ballegooy et al. (2014), otherwise the number of CPT soundings included in the analyses would have been very limited. In total 333 soundings were excluded from this study because they terminated at depth shallower than 10 m and it was unknown whether liquefiable soil was present below their termination depths. This resulted in a total of 535 CPT soundings being used in the liquefaction analyses.

The development of the groundwater model used to estimate the GWD in the liquefaction evaluations is detailed by El Kortbawi (2017). The GWD model generates a smooth surface and consequently is an approximate fit of the regressed data. Based on a comparison of predictions and measurements, the model provides the most accurate estimates of groundwater elevation at the center of the study area (i.e. Napier and Hastings). The prediction errors increase away from the center of the study area due to a reduction in the spatial density of available data.

3.3 *Predicted severity of liquefaction*

Using the input parameters discussed above, the BI14 CPT-based simplified liquefaction triggering procedure was used to compute the factor of safety against liquefaction (FS) as a function of depth at all CPT sounding sites. In turn, FS is an input into the LSN (van Ballegooy et al. 2014) liquefaction damage potential framework which considers the cumulative liquefaction response of the entire soil profile down to a maximum specified depth (z_{max}) in order to predict the severity of surficial liquefaction manifestations. LSN is defined as:

$$LSN = 1000 \int_0^{z_{max}} \frac{\varepsilon_v}{z} dz \quad (1)$$

where: ε_v is the calculated volumetric reconsolidation strain per Zhang et al. (2002); z is the depth below the ground surface in meters; and for this study $z_{max} = 10$ m. As may be observed from Eq. 1, the depth weighting factor is hyperbolic (i.e. $1/z$), resulting in significant weighting of shallow liquefied layers on the severity of surficial manifestations. Additionally, ε_v is both a function of FS and the density of the soil, and thus accounts for the contractive/dilative tendencies of the soil, and has a value greater than zero for FS < 2. The severity of the predicted surficial liquefaction manifestation increases with increasing LSN value (Table 1).

Table 1. LSN values used for damage classification (Tokin & Taylor 2016).

Severity Classification	Expected LSN
No Liquefaction	$LSN < 16$
Medium	$16 \leq LSN < 25$
High	$25 \leq LSN < 35$
Very High	$LSN \geq 35$

4 RESULTS AND DISCUSSION

Contour maps of computed LSN for Napier and Hastings for the 1931 Hawke's Bay earthquake scenario are shown in Figure 3. These maps are overlain with liquefaction observations made shortly after the 1931 earthquake, to facilitate comparisons of predicted versus observed liquefaction manifestations. Per Figure 3, Napier and its suburbs are predicted to have experienced severe liquefaction during the 1931 Hawke's Bay earthquake (LSN > 26), except for some locations in Ahuriri, Napier CBD, Tamatea, Maraenui, and Taradale where surficial liquefaction manifestations are predicted to be less severe. These lower severity predictions are possibly related to the soil density or depth distribution of liquefiable layers.

Despite the similarity in the shaking intensities experienced in Napier and Hastings (MMI X), the predicted severity of liquefaction is less for Hastings than for Napier (Figure 3). Possible reasons for this are the shallower GWD in Napier and that much of Napier is reclaimed swampland, reclaimed with loose sands and silts, resulting in profiles that are very susceptible to liquefaction. For example, Napier South was reclaimed in 1908 and the Ahuriri port area was reclaimed in 1878.

Based on Figure 3, more wide-spread liquefaction is predicted than was observed after the earthquake. This interpretation is based in part on the premise that if moderate or severe liquefaction did indeed manifest during the 1931 earthquake to the extent predicted, many more historical photos of these manifestations would have been taken (i.e. the absence of historical photos of liquefaction features in large regions somewhat implies that liquefaction did not manifest in a given region).

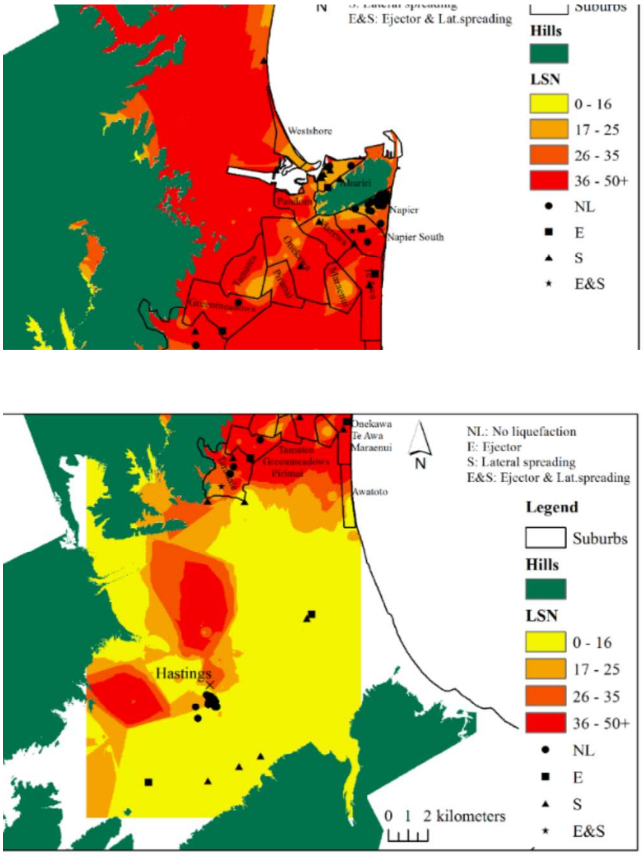

Figure 3. Distribution of predicted liquefaction severity, in terms of LSN, for the 1931 Hawke's Bay earthquake and post-earthquake observations in Napier (top) and Hastings (bottom).

To gain insights into possible reasons for the over-prediction of liquefaction severity, the Soil Behavior Type Index (I_c) (Table 2) (Robertson 1990) of the soil profiles in Napier and Hastings were computed and examined. Specifically, the average I_c over the upper 10 m of the profiles (i.e. I_{c10}) are examined because Maurer et al. (2015) showed that severity of surficial liquefaction manifestations in profiles in Christchurch having $I_{c10} \geq 2.05$ were often over-predicted during the 2010-2011 Canterbury Earthquake Sequence (CES). As may be observed from Figure 4, except for sites immediately west of Napier Hill and some dispersed sites in south Napier and Hastings (Hastings not shown in Figure 4), most of the profiles in the region have $2.05 \leq I_{c10} \leq 2.60$, indicating that the profiles are predominantly silty sand and sandy silt.

Soils with high fines content, and hence high I_c values, are generally more resistant to piping and hydraulic fracture and affect water flow and pore pressure development/dissipation among liquefied strata within the profile, and between liquefied strata and the ground surface (Maurer et al. 2015; Upadhyaya et al. 2018). As a result, the influence of the cumulative liquefaction response of profiles in Napier and Hastings having $I_{c10} \geq 2.05$ on the severity of surficial liquefaction manifestations is likely far less than is inherently assumed in the LSN framework, as well as all other existing liquefaction damage potential frameworks. Accordingly, the over-prediction of the severity of surficial liquefaction manifestations in the Napier and Hastings during the 1931 Hawke's Bay earthquake is consistent with the over-prediction in profiles in Christchurch having $2.05 \leq I_{c10} \leq 2.60$ that were subjected to shaking during CES.

Table 2. Boundaries of soil behavior type (Robertson 1990)

Soil Behavior Type Index, I_c	Soil Behavior Type
$I_c < 1.31$	Gravelly sand to dense sand
$1.31 < I_c < 2.05$	Sands: clean sand to silty sand
$2.05 < I_c < 2.60$	Sand mixtures: silty sand to sandy silt
$2.60 < I_c < 2.95$	Silt mixtures: clayey silt to silty clay
$2.95 < I_c < 3.60$	Clays: silty clay to clay
$I_c < 3.60$	Organic soils: peats

Other issues that could have added to the over-predictions are uncertainties in the input parameters into the liquefaction analyses (e.g. peak ground acceleration, ground water table depth, and representativeness of the profiles analyzed to those for which the post-earthquake liquefaction responses are known). However, these issues are considered to be of secondary or tertiary importance (El Kortbawi 2017) and are not discussed further herein.

5 CONCLUSIONS

Analysis of the computed LSN values for the study area shows that for the 1931 Hawke's Bay earthquake scenario, MMI X in both Napier and Hastings, the predicted liquefaction hazard in Napier is greater than in Hastings. This is due to the loose, sandy fill material in Napier used to reclaim swampland and the shallower groundwater table. A comparison of the predicted versus post-earthquake liquefaction response observations shows that the severity of surficial liquefaction manifestations is over-predicted in several areas of Napier and Hastings. This is likely due to the LSN framework having a tendency to over-predict the severity of surficial liquefaction manifestations in silty sand/sandy silt profiles prevalent in the region. Note, however, use of an alternative liquefaction damage potential framework would not resolve the over-prediction issue, because none of the existing frameworks are better suited to predict the severity of surficial liquefaction manifestations in silty sand/sandy silt profiles.

The tendency for existing procedures to over-predict the severity of surficial liquefaction manifestations for the 1931 Hawke's Bay earthquake due to the characteristics of the soil deposits is an important finding. This is because if the same types of analyses are performed to assess the region's liquefaction hazard due to future events, the hazard will also likely be over-predicted.

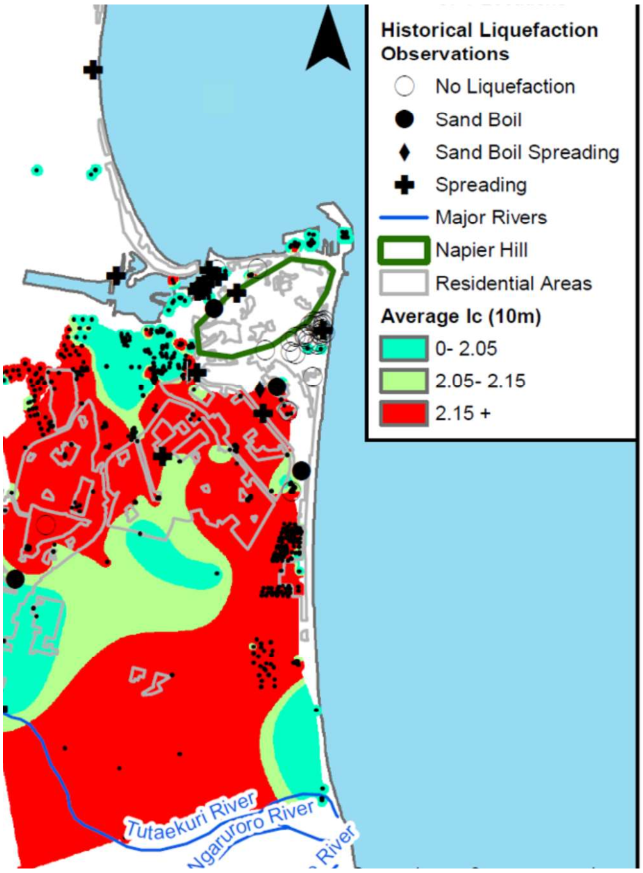

Figure 4. Average I_c in the upper 10 m in the soil profiles (i.e., I_{c10}) for Napier, superimposed by locations of CPT soundings used to compute the I_{c10} values and post-earthquake liquefaction observations.

6 ACKNOWLEDGEMENTS

This research was funded by National Science Foundation (NSF) grants CMMI-1435494, CMMI-1724575, and CMMI-1825189, the New Zealand Earthquake Commission (EQC), Tonkin & Taylor Ltd. New Zealand, the University of Auckland, Auckland, New Zealand, and Virginia Tech, Blacksburg, VA. Additionally, the authors gratefully acknowledge Mr. Rick Wentz who helped with the logistics in Napier and Hastings, the librarians and archivists at the MTG Museum, Napier Library, and Hastings Library who assisted in the collection of liquefaction observations, and historian Mr. Michael Fowler who helped with the collection of liquefaction observations. Also, Ms. Virginie Lacrosse from Tonkin & Taylor Ltd. ran the liquefaction calculator based on the specified input and provided the results presented discussed herein. This support and assistance are gratefully acknowledged. However, all opinions, findings, and conclusions or recommendations expressed herein are those of the authors and do not necessarily reflect the views of the NSF, EQC, or the others acknowledged above.

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