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Evaluating soil and landscape models to predict liquefaction susceptibility in the Hinuera Formation, Hamilton Basin

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ABSTRACT

Cone Penetration Tests (CPT) derived from the Hamilton section of the Waikato Expressway were analysed within CLiq^{TM} software. The derived Liquefaction Potential Index (LPI) from each CPT was then combined with LIDAR, pedological and geological maps for statistical analysis. A soil model that incorporates the conditions of modern soil development with these derived LPI values was developed as a preliminary assessment tool for liquefaction potential within Hamilton Basin soils. The model shows that liquefaction is more likely to occur on interfluvial areas where there is little topographical relief. Pedological soils with high organic component are also a likely indicator of high liquefaction susceptibility.

1 INTRODUCTION

Liquefaction is the process by which an increase in pore water pressure occurs from seismic stressors, resulting in loss of shear strength and resultant fluid-like behaviour of the affected soil (Obermeier, 2009). The ideal conditions for such an event include relatively recent (Holocene to Late Pleistocene) sediments that are cohesionless, dominated by coarse silt to fine sand, loosely packed, with a shallow water table (Eslami, Mola-Abasi, & Shourijeh, 2014; Owen & Moretti, 2011; Robertson & Wride, 1998). Within the Hamilton Basin, the Hinuera Formation comprises extensive Late Pleistocene (c. 22 to 17 cal ka) volcanogenic (mainly rhyolitic) alluvium dominated by unconsolidated and highly variable sediments, including pumiceous, ranging from cross-stratified gravelly or slightly gravelly sands, sandy gravels, and silts that show marked changes in lithology both vertically and horizontally over short distances (Hume, Sherwood, & Nelson, 1975). The Hinuera Formation has the potential to liquefy in the event of an earthquake because its physical properties in many places meet the criteria mentioned above. Paleoliquefaction features have occurred within the Hinuera Formation (Clayton & Johnson, 2013; Kleyburg, 2015). Pedological soils (at the land surface, usually to ~1 m depth) tend to reflect underlying characteristics of their parent materials in terms of texture, drainage, and water table level, these features being encompassed by 'soil family' for this particular study. A soil family is the fourth category in the New Zealand Soil Classification (NZSC) (Webb, 2011), with families being defined on the basis of physical properties, not genesis. These characteristics are also those which control the susceptibility, or otherwise, of subsurface materials to liquefaction. This paper investigates the thesis (following Kleyburg et al., 2015) that the mapped pedological soils on the surface of the Hinuera Formation provide a means of predicting the likely liquefaction susceptibility of a site.

2 METHODS

2.1 Site selection and data acquisition

The Hamilton Basin was chosen as the area of study because of the hazard a liquefaction event would pose to its many residents. The data were selected on the basis of availability from the New Zealand Geotechnical Database (NZGD), which provided a record of the initial CPT testing carried out before development began on the Hamilton section of the Waikato Expressway. LIDAR data were sourced from Waikato Regional Council. The pedological soil map was provided by Waikato Regional Council with the permission of Landcare Research. A total of 216 CPT data points were available in NZGD over a distance of ~18.5 km from Horsham Downs (north of Hamilton) to Tamahere (south of Hamilton).

2.2 CLiq^{TM} analysis

Raw CPT data were entered into CLiq^{TM} software to obtain the predicted Liquefaction Potential Index (LPI) developed by Iwasaki *et al.* in 1978 for assessing liquefaction potential based on the depth of the liquefiable layer in relation to ground surface as well as its thickness and its computed factor of safety (FS) (Toprak & Holzer, 2003). LPI is classified within CLiq^{TM} as either low (<5), moderate (5-15) or high (>15) potential based on the Robertson and Wride (NCEER 1998, 2009) calculation method for three separate depths of 3 m, 5 m and 10 m. Liquefaction potential (derived from LPI) was considered at a depth of 3 m as shallow liquefaction will be the most damaging in general, yet shallower materials are unlikely to liquefy due to lack of normal stress (Luo, Wang, & Li, 2013). A maximum depth of 10 m was considered because liquefaction deeper than this is likely to extend to the ground surface only for very large proximal earthquakes (Huang & Yu, 2013). The parameters used to compute LPI were derived from multiple sources. Input parameters included: horizontal peak ground acceleration (pga); earthquake moment magnitude (M_w); water table depth; and fines content. Horizontal pga was computed as 0.38 (g) using a_h = ZRC where Z (Hazard factor) = 0.16, R (Return period factor) = 1.8, and C (Site response factor) = 1.33 (NZ Transport Agency, 2014 & Technical Committee BD-006-04-11, 2004). A magnitude M_w = 7 event was assumed as worse-case selected from ranges of 5.5-7 M_w suggested for the Kerepehi Fault (Persaud et al., 2016; Wallace, Hamling, Holden, Villamor, & Williams, 2016). There is a relatively wide range within the literature regarding ground water table depth within the Hamilton Basin, with values as low as 0.6 m and as high as 4 m recorded in the field area. To account for water table level variation a depth of 1 m was used following the examples of Opus (2014) and (Ministry of Business Innovation and Employment, 2017; Opus, 2014) Fines content was also included in analysis as the finer component of a soil has a significant influence on liquefaction potential (Thevanayagam, 2000).

2.3 Data analysis

Data were compiled in Excel into a uniform format that could be easily imported into the software that would carry out analysis. The Excel spreadsheet consisted of each CPT having an appropriate label, alongside GPS coordinates, and the specific cumulative LPI values for 3, 5, and 10 m depths derived from the raw results of CLiq^{TM}. Factors of slope, elevation (derived from LIDAR DEM data), and soil families and associated soil siblings (defined by other physical properties and recorded using numbers) from S-map (Lilburne *et al*., 2011; Landcare Research, 2016) were included in the spreadsheet that was then imported into STATISTICA^{TM}. Soil families, identified by a geographical name with suffix *f*, are defined by the nature of soil profile material to 100 cm depth, parent rock (if present), dominant texture class to 60 cm depth, and permeability of the slowest horizon within 100 cm depth (Webb & Lilburne, 2011).

Parameters of LPI, slope, elevation, soil family and soil sibling were put into STATISTICA software to determine the most influential factors to liquefaction. Regressive Exhaustive CHAID (chi-square automatic interaction detection) was developed to identify and categorise parameters that are of higher influence to LPI where liquefaction potential was input as the predictive value (dependent variable), with slope, elevation and soil texture then input as continuous variables and soil family as a categorical variable (independent variables). The resultant graph then displays each independent variable as separate classes (low, moderate and high liquefaction potential) based on their associated LPI. Due to limited data availability some soil families only had one CPT test undertaken within them and therefore only one recorded LPI value. These families were not included within the analysis as only one LPI value could not faithfully represent the liquefaction potential for that particular family. GIS (Geographical Information Systems) was then used to depict the results from the statistical analysis in terms of liquefaction susceptibility.

3 RESULTS

3.1 CLiq^{TM} analysis

Liquefaction susceptibility, displayed as data points to the west of Hamilton City, show an increasing cumulative susceptibility with an increase in depth (Figure 1). At 3 m depth susceptibility is low (119 sites) to moderate (97 sites) with the majority of sites being considered as having a low susceptibility to liquefaction (LPI <5). At greater depths susceptibility can be seen to range from low to high with 10 m depths being dominated by high liquefaction susceptibility. When referring to Figure 1A, areas of moderate susceptibility appear more concentrated toward the southern end of the field area; within Figure 1B, high susceptibility appears within the middle/lower region of the field area also.

Figure 2 illustrates eight individual CLiq^{TM} output traces (3 m depth), with colours (see key) representing normalized Soil Behaviour Type (SBTn) and the yellow line indicating what the recorded soil behaviour was at each particular depth. These eight profiles were chosen because they illustrate how variation in soil behaviour can affect the resultant liquefaction potential, with each profile illustrating a different degree of LPI (from no liquefaction to moderate-high potential liquefaction occurrence). Profiles were derived from upper (northern), middle, and lower (southern) sections of the field area to give an accurate representation of entire data set.

Those that are of no to low susceptibility (Figure 2A & B) have a soil behaviour that is nearer to that of a granular soil or in contrast has a soil behaviour that is too-fines rich, typically >2.6 I_c (soil behaviour type index). As soil behaviour moves into more silt/sand textures susceptibility increases. The main difference that can be seen between those that read low moderate compared with those of high moderate is the influence of an increased fines content toward the top of the profile reaching a soil behaviour value of I_c ~2.6-3. Moderate susceptibility profiles show a similar pattern but do not exceed I_c=3, having a higher proportion of clay dominated fines.

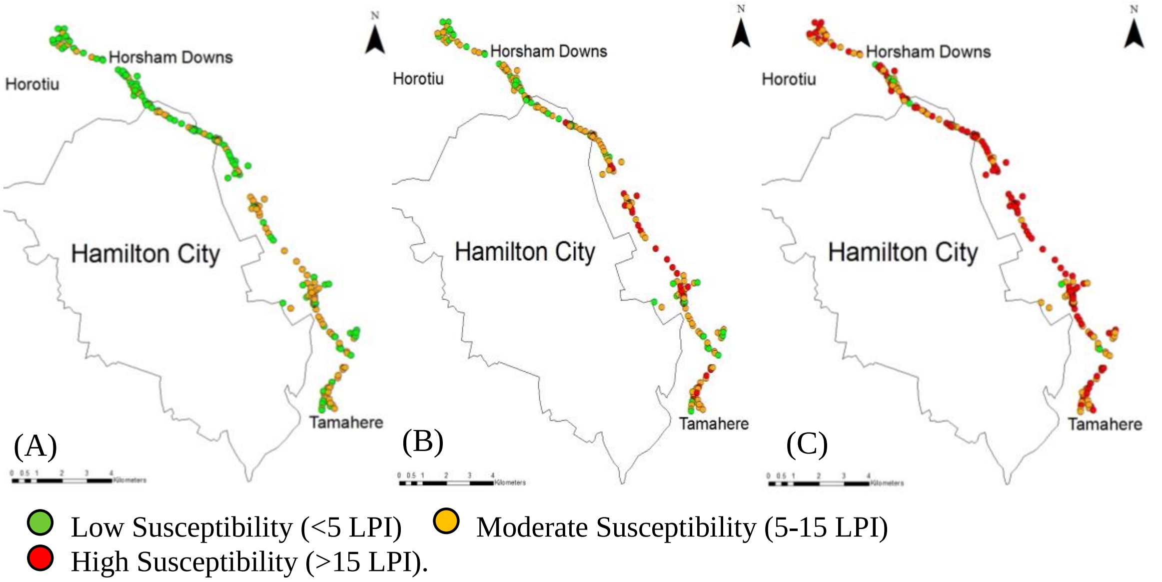

Figure 1. Field area (Hamilton city with Waikato Expressway Hamilton Section under construction to the east). Data points represent CPT sites and subsequent LPI based on Robertson and Wride (NCEER 1998, 2009) calculation method. (A) 3 m depth, (B) 5m depth, (C) 10 m depth.

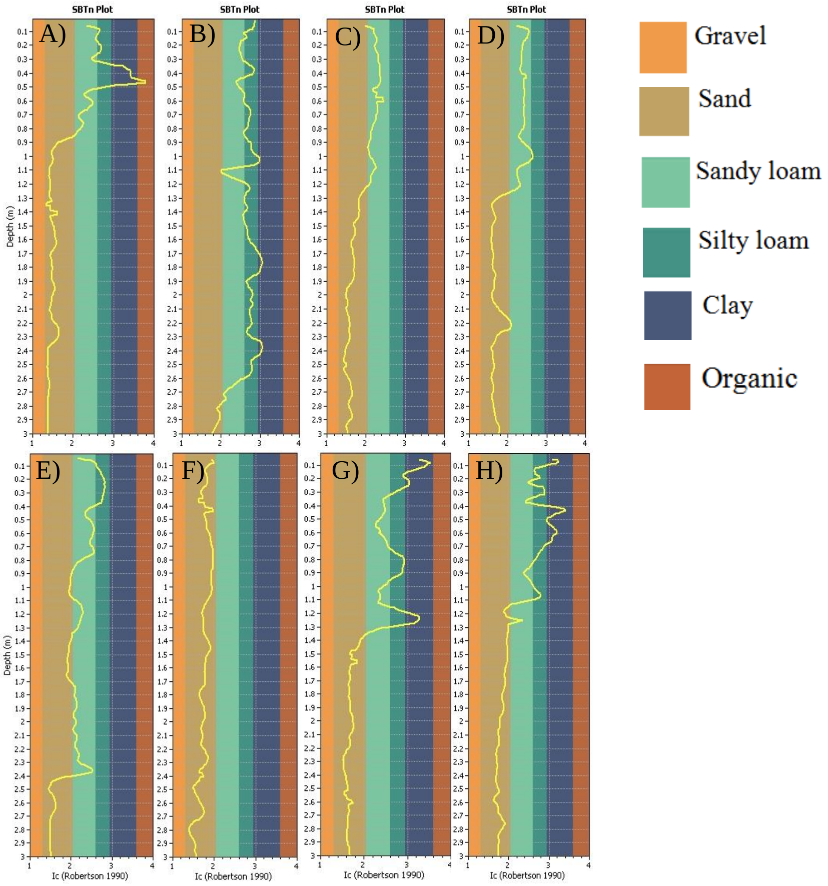

Figure 2. SBTn plots showing changes in proposed soil behaviour from 0.1- 3 m with each profile illustrating a different LPI value (Fig 2A-0, Fig2B-0.5, Fig2C-1.8, Fig2D-3.5, Fig2E-5.1, Fig2F-6.5, Fig2G-8.8 & Fig2H-11.28).

3.2 Statistical analysis

The results of the Exhaustive CHAID analysis can be seen in Figure 3. Of the independent variables, soil family, slope, elevation and sibling number, it can be seen that soil family is the most influential (dependent variable) when it comes to predicting liquefaction potential (shown in Figure 3 at 3 m depth but also shown at 5 m and 10 m depth when analysed). The soil families can be classified into three classes of liquefaction potential, low, medium and high. Pukehina*f*, Moeatoa*f*, Kohuratahi*f*, Kainui*f*, and Rotokauri*f* families are classified as low LPI (mean value of 3.72); Otorohanga*f*, Matakana*f*, and Te Puninga*f* families as medium LPI (mean value of 5.3); and Utuhina*f* and Kaipaki*f* families as high LPI (mean value of 7.57). Note, however, there is a relatively high variance within each LPI class (between 5–8), reflecting the variability within the soil families. With the exception of the high susceptibility node (ID 4–7.5 LPI) which terminates at soil family, the second most influential factor is elevation (Figure 3 has been ‘pruned’ for simplification and so does not show further splits based on less influential independent variables). For lower susceptibility soils (ID 2) elevation is, on average, higher than moderate susceptibility (ID 3) at approximately 36–38 m and 24–29 m, respectively. It is apparent from the data that liquefaction potential is at its highest when topography is less complex with little to no relief.

It can be seen within Figure 4, that on average, the susceptibility class predominantly ranges from low (green) to low-moderate (orange) with high-moderate values being confined to the Northeast of Hamilton City. The three main topographical features that can be identified on the surface of the Hinuera Formation are small ridges (mounds) up to a few metres in height, channels (paleo and current), and the interfluve zones (flat areas with little topographical relief). From Figure 4 it is apparent that when the topography becomes more complex the susceptibility is seen to decrease, such as in the drainage channels as well as along the low ridges. The areas that are displaying moderate to high susceptibilities are mainly within the interfluvial zone where ground is near to level.

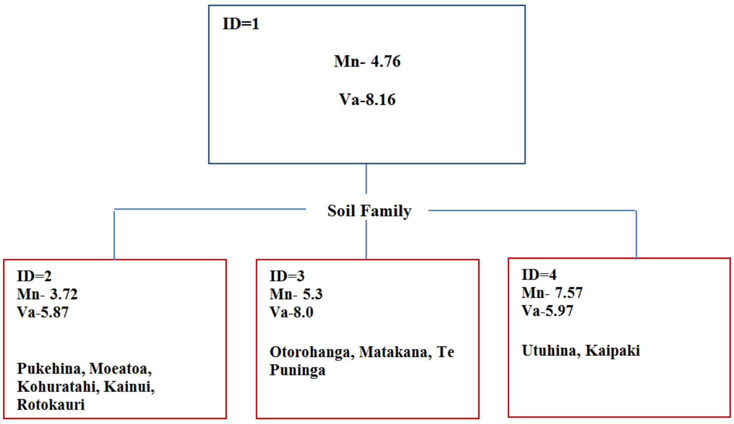

Figure 3. Exhaustive CHAID analysis at 3 m depths with ID 2 including Pukehina, Moeatoa, Kohuratahi, Kainui, Rotokauri families; ID 3 Otorohanga, Matakana, Te Puninga families; and ID 4, Utuhina, Kaipaki families. In the boxes, the mean LPI (Mn) and variance (Va) are shown.

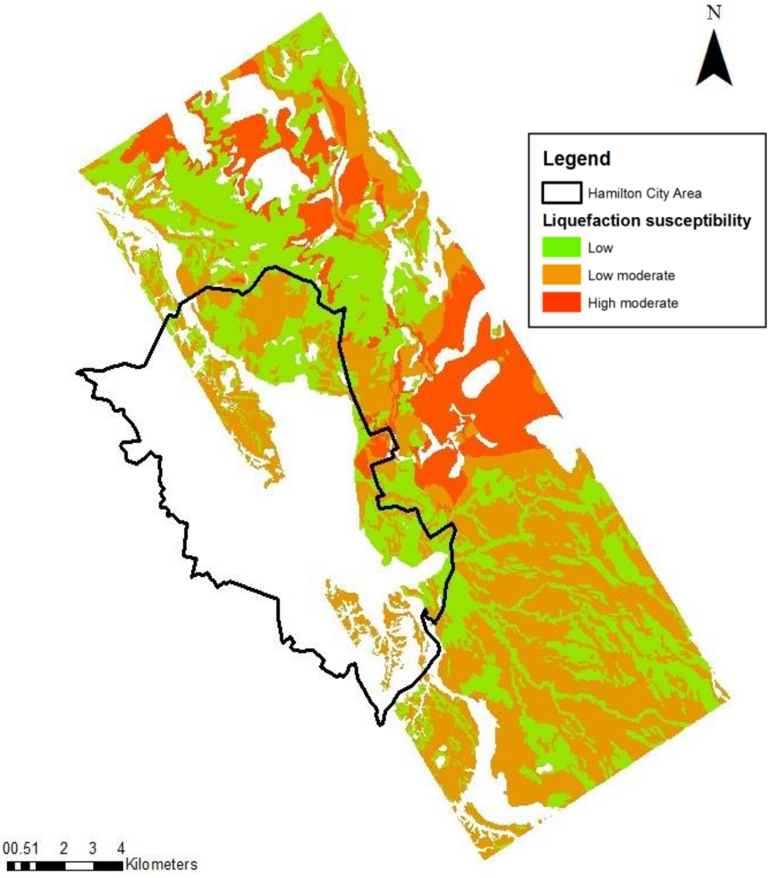

Figure 4. Generalised liquefaction susceptibility map of the Hamilton Basin based on STATISTICA analysis. Green= low susceptibility, Orange= low-moderate susceptibility and Red=high-moderate susceptibility.

4 DISCUSSION

Because of its alluvial origin, the Hinuera Formation is extremely diverse spatially in texture and sedimentary structure, and hence shows considerable lateral and vertical variability in liquefaction susceptibility. Typical stratigraphies show sand-dominated materials at the base, with an increase in fines content towards the upper profile. This upward decrease in grain size is expected when deposition is of alluvial origin, in particular a river channel that has changed course many times, as the grain size and pattern is indicative of flow dynamics with larger, more granular (clean sand) material being deposited where energy is at its highest (upstream or at depth), while finer grains are typically deposited closer to channel termination where shallowing occurs as a result of decreasing energy by decreasing gradient downstream (Nichols. G, 2009). This pattern of increasing fines within the upper profile is evident in the CPT data, however, the degree of fines does vary with some profiles showing more clay-dominated behaviors. Variability in LPI is likely due to differences in sand/silt/clay ratios so that mixed textures (silty sand/sandy silt) show a higher degree of liquefaction potential relative to profiles with predominantly sand (granular) or fines (clayey silt/silty clay) textures which generate lower LPI values.

It is important to take the soil behaviour derived from CLiq^{TM} as simply a guide and not a definitive conclusion, as it merely reflects the way the soil behaves in response to penetration with no empirical evidence from the texture itself. In addition, CLiq^{TM} may underestimate the degree of plasticity within soil (Robertson & Wride, 1998) as well as the crushability of pumiceous material, hence overestimating LPI due to lower computed soil resistance which is particularly important in the field area (Opus, 2013). In sites with sandy soil near to granular in nature (Figures 2A-D), low susceptibility is likely a result of increased cementation and grain size. The textures in Figures 2E-H appear closer to the sandy silt (I_c>2) boundary where it is likely to have a relative proportion of fines but still be sand dominated with limited plasticity. The predicted moderate LPI value would support the idea that an increase in fines is likely to increase liquefaction susceptibility (Ibrahim, 2014; Thevanayagam, 2000). The presence of a clay cap is also a factor that likely influences the predicted LPI values although this is not considered within CLiq^{TM} so empirical site specific information will be required to supplement this conclusion.

Statistical analysis showed that there may be a relationship between soil family and the underlying sediment (Hinuera Formation) that is subject to liquefaction. We postulate that factors and properties that influence pedological soil formation, such as water table level, soil texture, and topographic position, are similar vectors to those that influence liquefaction susceptibility. Both Utuhina and Kaipaki are organic soils formed on peat in permanently wet conditions (i.e., with high water tables) underlain by inorganic sand- and silt-rich alluvium. In our analysis, the Utuhina and Kaipaki soil families consistently have LPI values within the high-moderate range at all depths. Another significant factor of these soil families is that peat formation is indicative of a low relief (flat to gently undulating) because basin peat formation needs a level or slightly concave topography to sustain a saturated and therefore anoxic condition for partial organic matter decay (Dargie et al., 2017). A high water table is a prerequisite for liquefaction, and organic surface soils reflect this water table level as well as sand/silt mixtures being most likely to liquefy as shown by Cliq^{TM} analysis with the diverse nature of an alluvial system typically having these textures. While the organic soils or peats themselves are unlikely to liquefy, the underlying materials (Hinuera Formation) are potentially highly susceptible. The Hinuera Formation is the dominant alluvial deposit within the Hamilton Basin with more recent alluvial sediments only being found in close proximity to the Waikato River. Those soil families that were classified as having lower susceptibilities on average were more of a mixed texture and lacked that dominant organic component, suggesting lower water tables due to better drainage conditions, or a more complex topography. It can therefore be suggested the origin and texture of pedological soils (at the land surface) can indicate the physical conditions of the materials below and, in turn, provide a simple first-pass predictor of liquefaction susceptibility at a site. It is important to remember, however, that soil family attributes simply act as a guide to aid decision making on whether the site should be investigated further. Pedological soil is unlikely to liquefy itself due to it being at or near the surface and therefore lacking sufficient overburden for pore pressure build up under seismic stress.

With these observations it is possible that areas of potential significant liquefaction occurrence can now be identified in advance. Low-relief topography is a requirement for liquefaction occurrence, with the Hinuera Formation being the dominant soil parent material of the alluvial plains of the Hamilton Basin. Therefore, organic soils, such as Kaipaki*f*, underlain by Hinuera Formation, warrant further liquefaction testing based on the conclusions derived from our statistical analyses. This idea is further supported in Figure 4 with the higher liquefaction potential occurring on areas of lower relief and less complex topography, the areas in red being directly correlated to areas of localized peat bog formation. Liquefaction susceptibility is seen to decrease in drainage channels and on top of low ridges, and to increase on the flat interfluve areas. Drainage channels underlain mainly by coarser deposits that reflect high-energy river flow and hence are well drained. In contrast, decreased liquefaction potential on ridges is likely a result of increased overburden pressure as well as increased drainage due to slope gradient (Owen & Moretti, 2011).

5 CONCLUSION

We show that soil family, a pedological map class, provides a good initial indication of the physical conditions of the underlying liquefiable soil and therefore in turn liquefaction potential of land on the plains within the Hamilton Basin. Although the pedological soils will not, in themselves, liquefy in general, their modes of formation mean that they represent the underlying parent materials, water table levels, and local depositional environment. These characteristics are the key to generating soils that have high liquefaction potential, and hence the soil developed on a given lithology and topography will indicate the likely susceptibility of underlying sediments to liquefaction. From our analysis, it is suggested that the soil reflects liquefaction susceptibility to about 5 m depth; below this, changes in the lithologies are inevitable given the nature of alluvial fan deposition. As shallow liquefaction is likely to be the most damaging, the depths reflected in the soil profile will be those of greatest interest for many applications. For our study area, we recognize increased liquefaction potential in interfluve areas compared with channels or low ridges, and especially high potential in areas of low surface relief where peat bogs have formed. As soils and the pattern of liquefaction susceptibility are spatially highly variable, we appreciate that this division provides a general idea of the patterns of liquefaction susceptibility over a wide area: lateral variability means that specific sites may be different. The guide developed here does not replace site-specific investigation, but may help in targeting areas deserving more detailed assessment.

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REFERENCES

Clayton, P., & Johnson, J. (2013) Liquefaction Resistance and Possible Aging Effects in Selected Pleistocene Soils of the Upper North Island. In: Chin, C.Y. (ed). *Proc. 19th NZGS Geotechnical Symposium*, November 2013, Queenstown.

Dargie, G. C., Lewis, S. L., Lawson, I. T., Mitchard, E. T., Page, S. E., Bocko, Y. E., & Ifo, S. A. (2017) Age, extent and carbon storage of the central Congo Basin peatland complex. *Nature*.

Edbrooke, S.W. (compiler) 2005 *Geology of the Waikato area*. Institute of Geological and Nuclear Sciences 1:250,000 geological map 4. 68pp. + map sheet. IGNS, Lower Hutt.

Hewitt, A.E. (2010) *New Zealand Soil Classification 3rd ed*. Manaaki Whenua Press, Lincoln, 136pp.

Huang, Y., & Yu, M. (2013) Review of soil liquefaction characteristics during major earthquakes of the twenty-first century. *Natural Hazards*, 65(3), 2375-2384.

Hume, T. M., Sherwood, A. M., & Nelson, C. S. (1975) Alluvial Sedimentology of the Upper Pleistocene Hinuera Formation, Hamilton Basin, New Zealand. *Journal of the Royal Society of New Zealand*, 5(4), 421-462.

Kleyburg, M.A., Moon, V.G., Lowe, D.J., Nelson, C.S. (2015) Paleoliquefaction in Late Pleistocene alluvial sediments in Hauraki and Hamilton basins, and implications for paleoseismicity. *Proceedings, 12th ANZ Conference on Geomechanics*, 22-25 February, 2015, Wellington, pp. 524-531.

Landcare Research (2016) *S-map online: the digital soil map for New Zealand* (https://smap.landcareresearch.co.nz/)

Lilburne, L.R., Webb, T.H., Hewitt, A.E., Lynn, I.H., de Pauw, B. (2011) S-map database manual. *Landcare Research Report LC478*, 61 pp.

Luo, Q., Wang, C. Y., & Li, X. W. (2013) Experimental Study on Silt Liquefaction Characteristics of Different Fines Content. In *Applied Mechanics and Materials* (Vol. 353, pp. 2323-2326). Trans Tech Publications.

New Zealand Geotechnical Society (2016) Earthquake geotechnical engineering practice. MODULE 1: Overview of the guidelines.

NZ Transport Agency (2014) The NZ Transport Agency's Bridge manual. Site Stability, Foundations, Earthworks and Retaining Walls: 6-7.

Obermeier, S. F. (1996) Use of Liquefaction-Induced Features for Paleoseismic Analysis. *Engineering Geology*, 44(1-4), 1-76.

Obermeier, S. F. (2009) Using Liquefaction Induced and Other Soft Sediment Features for Paleoseismic Analysis. *International Geophysics*, 95, 497-564.

Opus. (2013) Ruakura Development: Stage 1 Geotechnical Investigation. Retrieved from New Zealand: http://www.epa.govt.nz/resource-management/NSP000034.

Opus (2014) Waikato Expressway: Hamilton Section, Ruakura Interchange: Assessment of Water Effects. Retrieved from Hamilton New Zealand: http://www.hamilton.govt.nz/ourcouncil/councilpublications/operativedistrictplan/Documents/Ruakura%20Interchange/2H%20FINAL%20Stormwater%20Report.pdf.

Owen, G., & Moretti, M. (2011) Identifying Triggers for Liquefaction-Induced Soft-Sediment Deformation in Sands. *Sedimentary Geology*, 235(3), 141-147.

Persaud, M., Villamor, P., Berryman, K., Ries, W., Cousins, J., Litchfield, N., & Alloway, B. (2016) The Kerepehi Fault, Hauraki Rift, North Island, New Zealand: active fault characterisation and hazard. *New Zealand Journal of Geology and Geophysics*, 59(1), 117-135.

Robertson, P., & Wride, C. (1998) Evaluating Cyclic Liquefaction Potential using the Cone Penetration Test. *Canadian Geotechnical Journal*, 35(3), 442-459.

Technical Committee BD-006-04-11. (2004) New Zealand Standard, *Structural Design Actions, Part 5: Earthquake actions*.

Thevanayagam, S. (2000) Liquefaction potential and undrained fragility of silty soils. *Proceedings of the 12th World Conference Earthquake Engineering*, Wellington, New Zealand.

Toprak, S., & Holzer, T. L. (2003) Liquefaction potential index: field assessment. *Journal of Geotechnical and Geoenvironmental Engineering*, 129(4), 315-322.

Wallace, L. M., Hamling, I., Holden, C., Villamor, P., & Williams, C. (2016) Introduction to NZJGG special issue in honour of John Beavan's scientific contributions.

Webb, T. H., Lilburne, L.R. (2011) Criteria for defining the soil family and soil sibling – the fourth and fifth categories of the New Zealand Soil Classification. *Landcare Research Science Series No. 3 (2nd ed)*. 38pp.