Paleoliquefaction in Late Pleistocene alluvial sediments in Hauraki and Hamilton basins, and implications for paleoseismicity

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ABSTRACT

Liquefaction susceptibility of the Late Pleistocene Hinuera Formation is of interest to the engineering community as it is unclear whether materials of this age will still be prone to activation by cyclic stresses. In this paper we report on rare paleoliquefaction features in the form of injection structures that we have identified at two sites near Hamilton. These structures are clearly earthquake induced, and indicate the potential for future liquefaction episodes. However, we suggest that the hazard is restricted to areas with impeded drainage that imparts a high water table. Such areas are localised, and may be recognised from the modern (pedological) soil distribution. Evaluating piezocone penetration test (CPTu) data from the sites of known paleoliquefaction indicates that the CPTu gives a meaningful indication of liquefaction potential, and questions the validity of applying aging factors to these deposits.

Keywords: paleoliquefaction, liquefaction, alluvial sediments, Late Pleistocene, Hinuera Formation, Hamilton Basin, Hauraki Basin, Kerepehi Fault, paleoseismicity

1 INTRODUCTION

Liquefaction events during the Canterbury earthquake sequence in 2010 to 2011 have emphasised the severity of liquefaction as a potential hazard for all New Zealand communities. A large proportion of the urbanised areas of the Hamilton and Hauraki basins (Figure 1) are underlain by the Hinuera Formation, extensive, low-angle Pleistocene alluvial fan deposits that possess characteristics suggestive of high liquefaction susceptibility. In particular, loose unconsolidated fine sands and silts are accompanied by localised areas of high groundwater and, in the Hauraki Basin, the presence of the active Kerepehi Fault, features that may result in liquefaction under cyclic stresses. However, the latest phase of deposition of the Hinuera Formation (in the Hamilton Basin) occurred ~22,000 to ~18,000 years ago in the Late Pleistocene (McCraw 2011). In general, sediments of recent (<500 years) and Holocene (last 11,700 years) age are recognised as being at most risk of liquefaction, whilst only a few reports of liquefaction occurring in Late Pleistocene deposits have been recorded (e.g. Obemeier 1998). Consequently, screening methods for assessing liquefaction susceptibility based on age and geological origin suggest relatively low (Youd and Perkins 1978) susceptibility, in contrast with instrumental methods such as CPTu which suggest much higher susceptibility (Clayton and Johnson 2013).

Paleoliquefaction features are geological structures within a sedimentary sequence that are recognised as forming as a consequence of movement of material during a liquefaction event. They are commonly recognised as injection structures, which form sand dikes or sills that intrude through subsequent layers, although liquefaction may also be manifested by distortion of sediment layers. Bastin et al. (2013) presented a summary of liquefaction structures produced by the recent Christchurch earthquake sequence (2010−2011). Previous studies on sedimentary features of the Hinuera Formation identified uncommon secondary sedimentary structures including corrugated laminations, irregular synclines and anticlines, diapiric distortions, expulsion structures, and flame structures (Sherwood 1972; Hume et al. 1975), all of which are suggestive of sediment migration under fluidised conditions. At that time it was uncertain whether such features were post- or syn-depositional in origin.

The aim of our research is to assess liquefaction using geological methods, thus identifying whether paleoliquefaction features occur in the Hinuera Formation. The identification of such features led us to evaluate the viability of instrumental methods, such as CPTu, to provide a method of predicting liquefaction potential.

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2 GEOLOGICAL SETTING OF THE STUDY AREA

2.1 Hinuera Formation

The Hinuera Formation comprises volcanogenic alluvium deposited as large, low-angle fans by a high-energy, braided ancestral Waikato River firstly in the Hauraki Basin (prior to ~22,000 years ago) and then in the Hamilton Basin from ~22,000 to ~18,000 years ago (McCraw 2011). The Hinuera deposits are highly variable and complex and vary both laterally and vertically in both basins, and hence no two sites are identical. Material accumulated rapidly, forming thick deposits of cross-bedded gravels, gravelly sands, sands, and silts together with interbedded peats (Schofield 1965; Hume et al. 1975; Kear and Schofield 1978; McGlone et al. 1978; Houghton and Cuthbertson 1989). The most active phase of deposition occurred after eruption of the Kawakawa (Oruanui) tephra ~25,400 years ago (Vandergoes et al. 2013) when huge volumes of loose pyroclastic materials, and break-out flood deposits, from the eruption were reworked over several millennia at least, and the ancestral Waikato River avulsed from its long-established route through the Hauraki Basin into the Hamilton Basin ~22,000 years ago (Manville and Wilson 2004; Manville et al. 2007). Ages used to help constrain this depositional history are summarised mainly in Manville and Wilson (2004) and are based on radiocarbon dating and tephrochronology (e.g. see Hogg et al. 1987; McCraw 2011). Today these Hinuera deposits underlie the gently sloping land surfaces of the alluvial fans over large areas of the Hamilton and Hauraki basins, referred to as the Hinuera Surface (Schofield 1965; Selby and Lowe 1992; Manville and Wilson 2004).

2.2 Hauraki Basin

The Hauraki Basin, infilled in part by the Hinuera Formation, extends from Tirau to the Firth of Thames (Houghton and Cuthberston 1989). The basin is bounded by the Firth of Thames Fault in the west, the Hauraki Fault in the east, and the Kerepehi Fault runs through the central part of the basin (Figure 1) (Hochstein and Nixon 1979; Beanland et al. 1996; Leonard et al. 2010). The active Kerepehi Fault has moved at least four times in the Holocene, c. 10,000, c. 7600, c. 6400, and c. 1300 years ago (de Lange and Lowe 1990). According to Hochstein and Nixon (1979), transverse faults cross the Hauraki Basin causing horizontal offsets of the main faults noted above.

2.3 Hamilton Basin

The Hamilton Basin, infilled partly by the Hinuera Formation, is an oval-shaped depression that extends from near Te Awamutu to Taupiri. The basin is bounded by the Waipa Fault to the west but no faults are known within the Hamilton Basin (other than old faults inferred in underlying basement rocks: Edbrooke 2005).

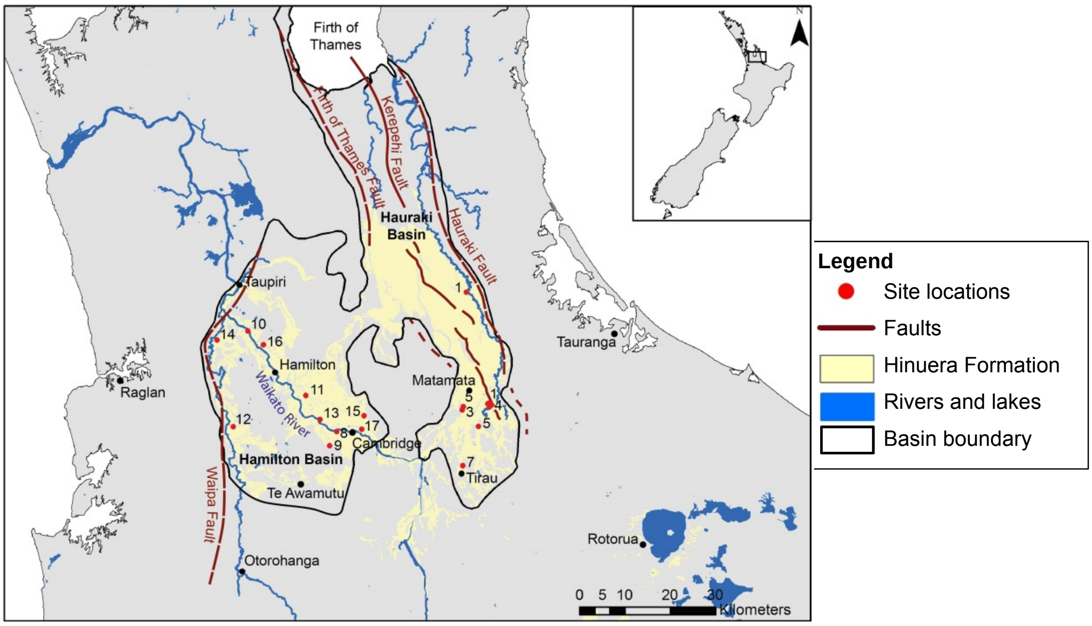

Figure 1. Map showing distribution of Hinuera Formation in Hauraki and Hamilton basins (after Edbrooke 2005; Leonard et al. 2010) and site locations (Table 1)

3 METHODS

A total of 17 sites were visited in the Hauraki and Hamilton basins (Figure 1). The sites comprised commercial sand quarries, privately owned sandpits, and construction sites (Table 1), with six in the Hauraki Basin and 10 in the Hamilton Basin.

At each site detailed geological descriptions and stratigraphic logs were constructed. Sites containing evidence of definite paleoliquefaction features were sampled for particle size analysis and radiocarbon dating in conjunction with piezocone penetration tests. For the particle size analysis, samples of the material infilling injection structures, and the surrounding sediments, were collected and analysed using a Malvern laser sizer. Samples were categorised according to the Udden-Wentworth grain size scale, which has boundaries similar to those of the NZGS (2005) guidelines. A total of eight CPTu tests were drilled to depths of 20 m. Liquefaction susceptibility was determined using the methods of Idriss and Boulanger (2008). Organic materials from sites containing paleoliquefaction features were dated using the radiocarbon technique at the Waikato Radiocarbon Dating Laboratory. Pre-treatment of organic silt fractions for dating included an acid-base-acid wash.

Table 1: Sites visited with secondary sedimentary structures identified. Coordinates in NZTM2000.

Number	Site	Co-ordinates (e/n)	Structures
1	Private Property – Kevin Nola	1848089, 5808490	Microfaulting
2	McPhersons Sand Supply	1846039, 5803451	-
3	Daltons Sand Ltd	1842467, 5807094	-
4	Private Property – Ian Settle	1848444, 5807808	-
5	Wilson Sand / Wilson Resources Ltd	1842718, 5807793	-
6	Manawaru Sandfill and Livestock Ltd	1843367, 5833143	-
7	Tirau Sand Quarry	1842541, 5794762	Small scale sand injections
8	Landcycle – The Quarry Group	1814766, 5802279	-
9	Monavale Sand Quarry	1813165, 5799227	Possible rotated blocks
10	Perry Resources	1795115, 5824566	-
11	Waikato Aggregates	1807873, 5810298	-
12	L A and D A Coombes Sand	1791890, 5803412	-
13	Porrits	1811054, 5804979	-
14	Wedding I H and Sons Waikato Ltd	1788293, 5822524	-
15	Quarry on Aspin Road – Will Hjorth	1820745, 5805814	Injection structures
16	Endeavour Primary School	1798577, 5821506	Injection structures
17	Southern Links (Waikato Expressway)	1820267, 5802862	-

4 RESULTS

All but two of the sites visited contained no definitive evidence of paleoliquefaction features. Within the Hauraki Basin, the sediments are characteristically pumiceous gravels or sands and often cross-bedded, but despite the presence of the Kerepehi Fault, known to have been active in the Holocene at least (de Lange and Lowe 1990), only one out of the seven sites showed possible evidence of paleoliquefaction features. This was at Tirau Sands (site 7) where the water table is high. In the Hamilton Basin, the sediments characteristically are mainly cross-bedded gravels (predominantly rhyolitic) and sands. Two sites out of 10 showed clear evidence of past liquefaction: (1) site 15, a quarry on Aspin Road near Cambridge, and (2) site 16, an excavation pit associated with construction of the new Endeavour Primary School in Hamilton.

4.1 Site 15 – Quarry on Aspin Road

4.1.1 Injection structures

A prominent injection structure occurs intruding through four sedimentary units on an excavated quarry wall in the sand quarry on Aspin Road near Cambridge (Figure 2). The quarry wall is part of an embankment adjacent to a flocculation pond. The injection structures start at a depth of 1.5 m below the present quarry floor, which is approximately 3.5 m below the pre-excavated land surface. The stratigraphy identified in the field shows the liquefied source material at the base (Sand-1). This is overlain by Silt-1, Organic silt, Silt-2, Sand-2, and Sand-3. The injection structure cuts through the silts and organic material where it eventually splays into two different directions (Injection-1 and Injection-

2a) in the overlying sand layer. Water level is indicated by the flocculation pond to be 2 m below the present quarry floor. Other injection structures were observed but not all were sampled because of rapid quarry cutting.

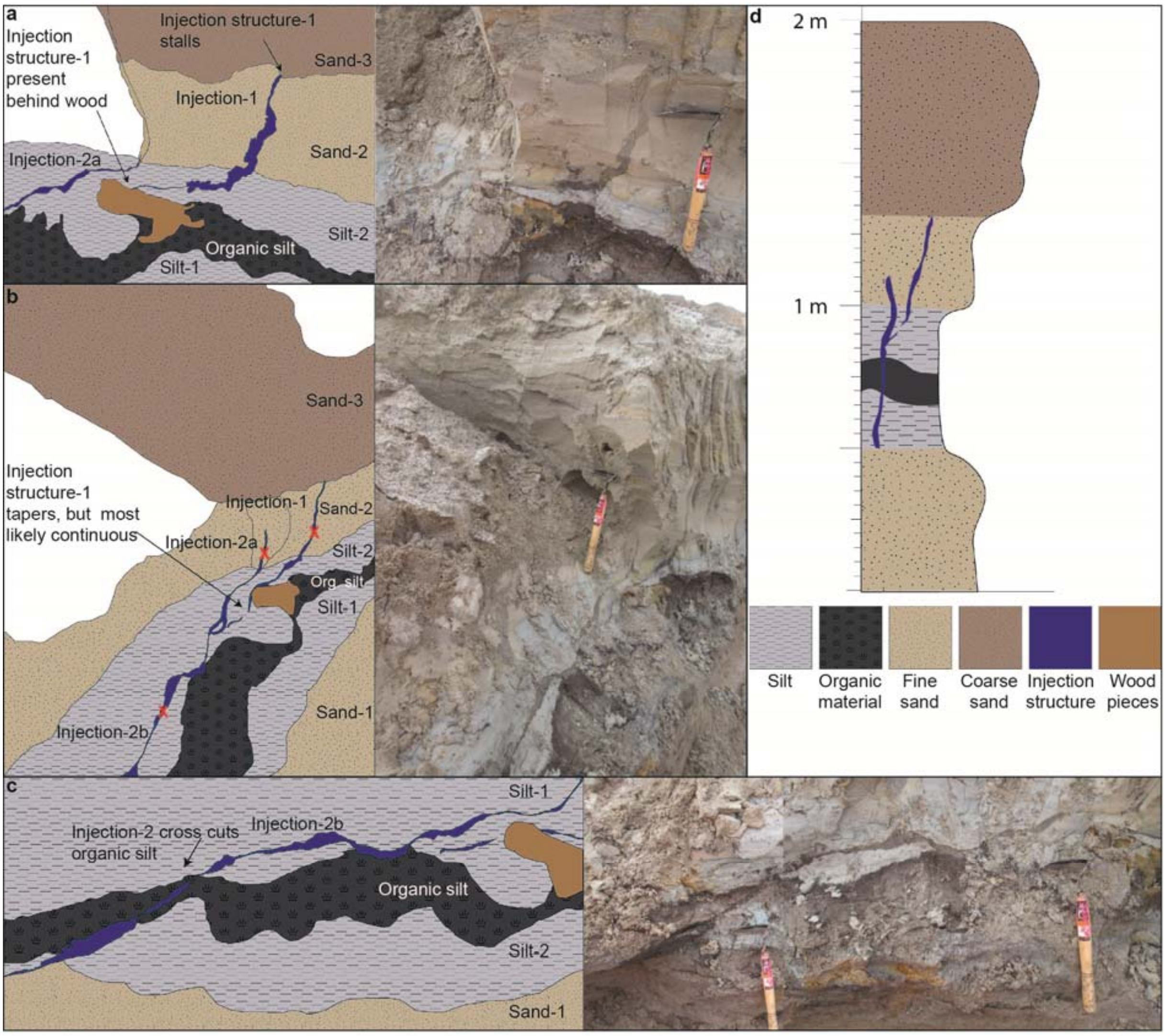

Figure 2. Injection structures for Site 15. (a) Injection-1 intrudes through Silt-1 and Sand-2; width: 0.03 m; vertical height: 0.30 m; horizontal length 0.48 m. (b) and (c) Injection-2 intrudes through Silt-1, Organic silt, Silt-2, and Sand-2; width: 0.01-0.02 m; vertical height: 0.10 m; horizontal length 1.20 m. Sample sites are indicated by the red X. (d) Stratigraphy at Site 15. Cutting tool is ~30 cm in length.

4.1.2 Particle size analysis

Six layers were sampled (Sand-1, Silt-1, Organic silt, Silt-2, Sand-2, and Sand-3) (Figure 2b) for particle size analysis. The injection structure was sampled in three places: one at its lateral position (Injection-2b), and two at its vertical position (Injection-1 and Injection-2a) (Figure 2a).

The cumulative frequency grain size plots show that the injection structures and the lower sand unit (Sand-1) are clearly within the boundaries of a high possibility of liquefaction (Figure 3). The particle size analysis strongly suggests Sand-1 is the source material for the injection structures because of the similar cumulative frequency curves. Sand-3 could possibly liquefy, it may be too high in the stratigraphic sequence. In contrast, the silts and Sand-2 units are less likely to liquefy.

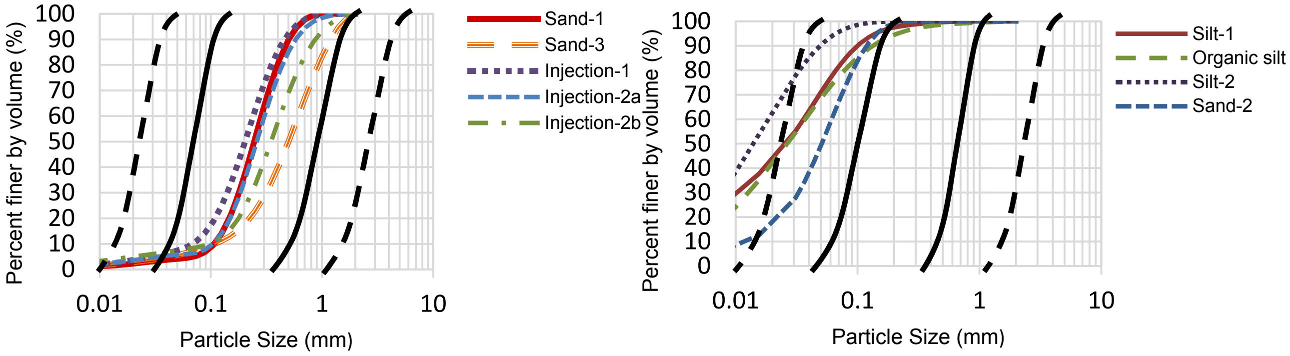

Figure 3. Cumulative plot of particle size distribution of samples from Site 15. Black solid line indicates limits of high potential for liquefaction, dotted boundary indicates possible liquefaction limits (Ministry of Transport Japan 1999)

4.1.3 Liquefaction assessment using CPTu

Two piezocone penetration tests were conducted at this site, one near the injection structures from the present quarry floor and the second at a location that encompassed the stratigraphic units below the quarry excavation. The depth at which the liquefaction structure was found indicates a high liquefaction potential and 0.6 factor of safety (Figure 4a).

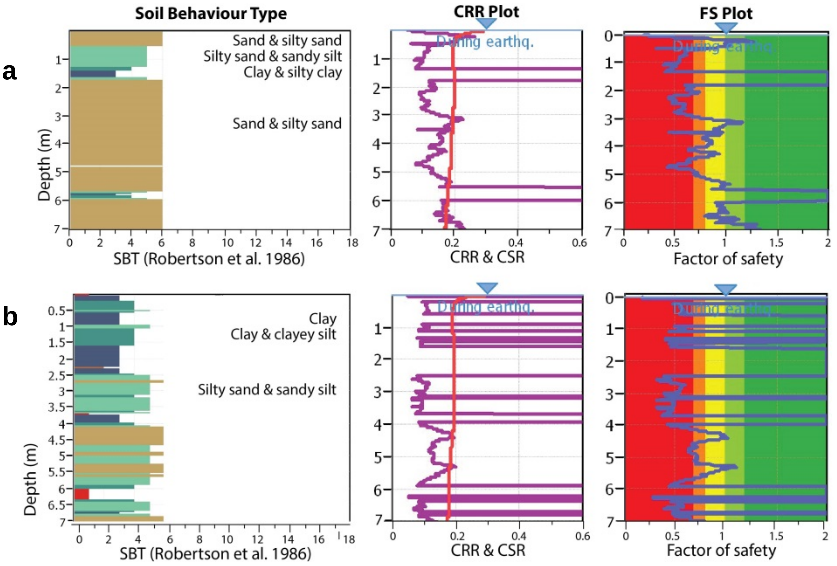

Figure 4. Soil behaviour type (SBT), cyclic resistance ratio and cyclic shear ratio (CRR & CSR) and factor of safety (FS) plots of (a) CPTu-1 for site 15 and (b) CPTu-6 for site 16 conducted in CLiq (GeoLogismiki 2006)

4.1.4 Radiocarbon dating

The ages obtained at both sites 15 and 16 (Table 2) provide an estimate of the age of deposition of the materials, and hence pre-date the liquefaction structures (through the principle of cross-cutting relationships). The three Aspin Quarry (site 15) dates are identical, and thus a seismic event occurred sometime after c. 20,749 ± 204 calendar yr BP, the mean age (± 2 sd) of the three Aspin Quarry ages (Wk39953 to Wk39955) combined using the *R_combine* function of OxCal (Bronk Ramsey 2001).

Table 2: Radiocarbon dates for organic material at site 15 (AP) and site 16 (EN).

Site	Lab sample number[1]	Material type	Radiocarbon age (^{14}C yr BP ± 1sd)[2]	Calibrated age (calendar yr BP, 94.5 % prob range)[3]
AP-1	Wk39953	Organic silt	17,278 ± 105	20,801 ± 301
AP-2	Wk39954	Organic silt	17,294 ± 85	20,813 ± 258
AP-3	Wk39955	Organic silt	17,158 ± 94	20,655 ± 280
EN-1	Wk39956	Peat	16,601 ± 58	19,964 ± 222

[1]Waikato dating lab number; [2]BP, before present, 'present' being AD 1950; [3]Calibrations based on OxCal v4.2.4 (Bronk Ramsey 2001, updated online 2013) and SHCal13 (Hogg et al. 2013)

4.2 Site 16 – Endeavour Primary School

4.2.1 Injection structures

Multiple liquefaction features were recognised in plan-view across the Endeavour Primary School site 16. Two localities containing swarms of paleoliquefaction features have been identified (locality i and ii, Figure 5). At each locality, a pit was excavated bisecting a paleoliquefaction feature to provide a cross-sectional view. The pit at locality i demonstrates an injection structure intruding through three sedimentary units: a sand, a peat, and a silt layer. These injection structures occur at a depth of 3 m below the pre-excavated surface. The pit at locality ii shows the injection structures intruding through a thick sandy-silt layer. These paleoliquefaction features are found at depths of 3.6 m from the pre-excavated surface. The water table was situated at the base of the locality ii pit at a depth of 3.8 m below the original surface.

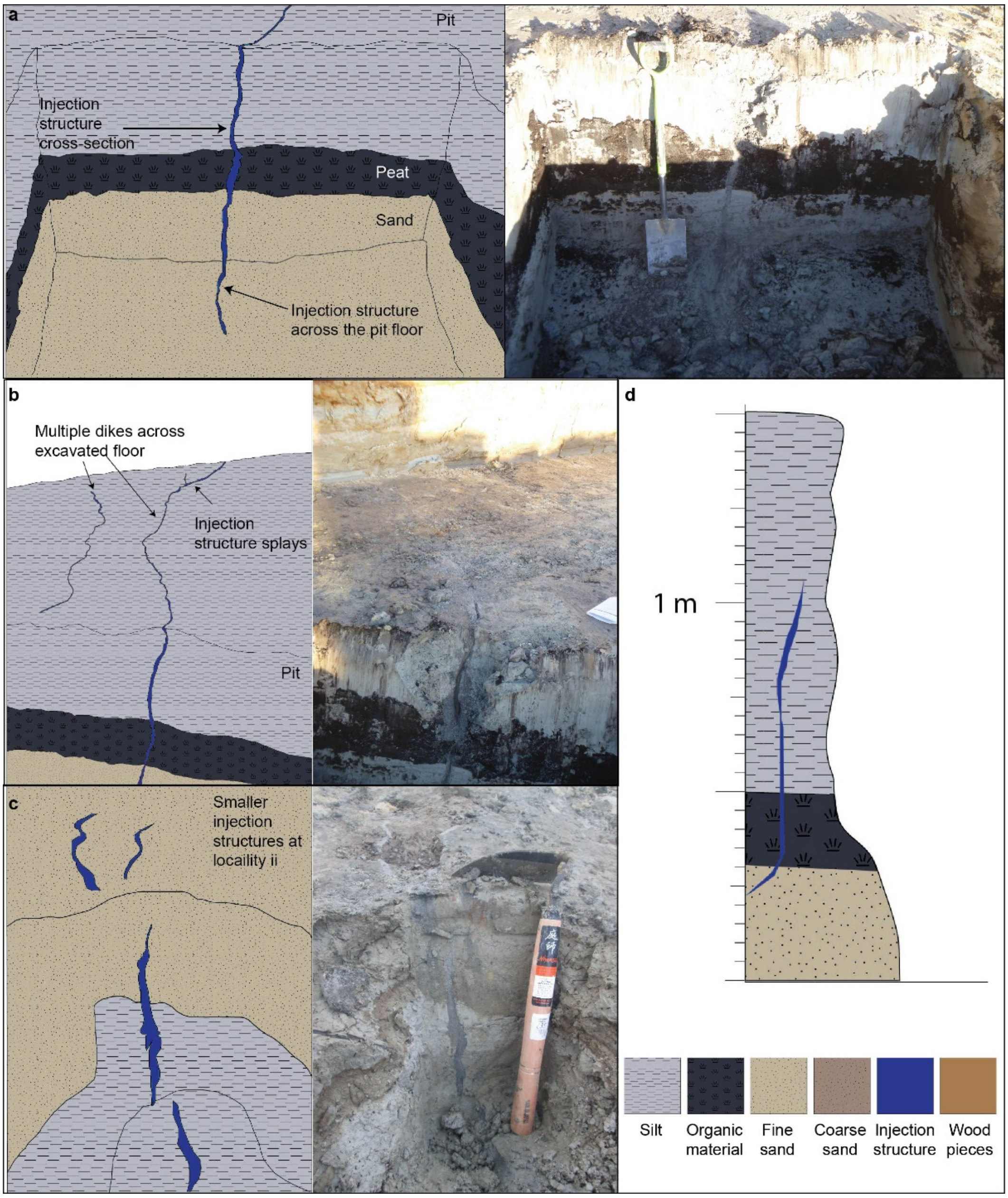

Figure 5. Injection structures for Site 16. (a) and (b) are at locality i, injection structure intrudes through peat and silt layers. Width: 0.03 m; vertical height: 1.10 m; horizontal distance: 3.30 m. (c) at locality ii, injection structure intrudes through sandy-silt layers. Width: 0.02 m; vertical height: 0.04 m; horizontal length: 0.05 m. (d) Stratigraphy at locality i. Cutting tool ~ 30 cm long, spade ~ 1 m in length

4.2.2 Particle size analysis

The sand layer (Sand) and the paleoliquefaction feature (Injection) were sampled at locality ii for particle size analysis (Figure 6). The cumulative grain size plot indicates that the Sand layer will liquefy under the right conditions and is clearly the source of the injection structure.

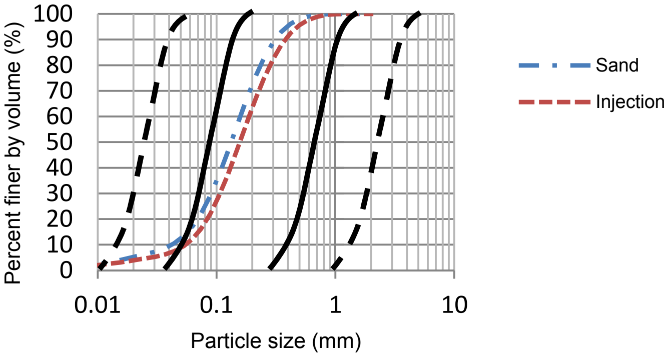

Figure 6. Cumulative particle size distribution of Endeavour Primary School samples. Black solid line indicates limits of high potential for liquefaction, dotted boundary indicates possible liquefaction limits (Ministry of Transport Japan 1999)

4.2.3 Liquefaction assessment using CPTu

As part of the preliminary ground investigation, six CPTu tests were undertaken. CPTu-6 is adjacent to the injection structures at locality i and CPTu-3 is near locality ii. The materials at the depth at which liquefaction was found at locality i show a high liquefaction potential and factor of safety (FS) of 0.4. Similarly, sediments at locality ii show a high liquefaction potential and a FS of 0.25 (Figure 4b).

5 DISCUSSION AND CONCLUSION

The majority of investigated sites in the Late Pleistocene alluvial sediments of the Hinuera Formation do not show evidence of past liquefaction, especially within the Hauraki Basin where deposits are more pumiceous. However, two sites (15 and 16) in Hamilton Basin show injection structures that intrude through several overlying layers. We thus infer that these structures are associated with earthquake liquefaction rather than syn-depositional processes. The two sites with clear evidence of past liquefaction exhibit common features of an elevated water table and fine sands underlying organic-rich layers: in both cases the fine sand has liquefied and been injected into and through the organic-rich materials. Saturated soils are a pre-requisite for liquefaction, and so the observation of a high water table is unsurprising. However, it is notable that these sites were the only ones in the Hamilton Basin where the water table was at a shallow depth. The Tirau site (site 7) in the Hauraki Basin also displayed a shallow water table. At this site a possible injection structure was observed but it was too small to be convincingly of an earthquake origin. Therefore, we infer that the present-day liquefaction hazard is localised, but exists in all of those areas where a high water table is present.

Silt and organic layers are important indicators of impeded or slow drainage, thus generating high water tables. Silts originated usually as overbank flood deposits (Hume et al. 1975) and are commonly linked with subsequently-developed peats, and, if near the present-day land surface, are reflected in the modern pedological soil pattern (e.g. Bruce 1979). The liquefaction structures observed were both associated with the silty Te Rapa and Te Kowhai soil series, which occur in topographic depressions on the Hinuera Surface. This relationship raises the possibility of developing a soil-landscape model using the modern soils to predict areas of likely high susceptibility to liquefaction; this work is ongoing.

The liquefaction assessment provided by the CPTu data is consistent with the depth at which paleoliquefaction is found. Site 15 is most consistent showing a high liquefaction susceptibility, a low FS, and the stratigraphy based on Soil Behaviour Type is similar to that observed in the field. Site 16 demonstrated a high liquefaction susceptibility and a low FS at depths at which paleoliquefaction was found, but the stratigraphy did not correspond with field observations. This mismatch is most likely due to the variability of sedimentary units on site and the distance of the CPTu test from the injection structures. At both sites the organic material clearly evident on site was not recognised in the CPTu data. We conclude that the instrumental CPTu method provides a valid method of predicting liquefaction potential, but does not adequately recognise the organic-rich layers that are associated with the paleoliquefaction features recognised at both key sites. However, on the basis of these observations, there is little justification for assuming an “aging” factor in the liquefaction potential analysis. A better constraint on the age of the events that generated the observed structures would help to determine the validity or otherwise of the aging factors commonly applied.

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