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Utilizing piezovibrocone in marine soils at Tauranga Harbor, New Zealand

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Abstract. Piezovibrocones have been developed to evaluate the liquefaction potential of onshore soils, but have not yet been utilized to evaluate the *in-situ* liquefaction behavior of offshore marine and volcanoclastic sediments. Two static and vibratory CPTu (Cone Penetration Tests) were performed at Tauranga Harbor, New Zealand. The lithology is known from nearby drillholes and the influence of vibration on different types of marine soils is evaluated using the reduction ratio (*RR*) calculated from static and vibratory CPTu. A sediment layer with high potential for liquefaction and one with a slight reaction to cyclic loading are identified. In addition to the reduction ratio, the liquefaction potential of sediment is analyzed using classic correlations for static CPTu data, but no liquefaction potential was determined. This points to an underestimation of liquefaction potential with the classic static CPTu correlations in marine soil. Results show that piezovibrocone tests are a sensitive tool for liquefaction analysis in offshore marine and volcanoclastic soil.

Keywords: Piezovibrocone; marine soils; *in-situ* and liquefaction

1. Introduction

Soil liquefaction is an important hazard for marine infrastructure and may be initiated by dynamic stresses in the marine environment such as waves, earthquake activity, machine vibrations etc. (Davis and Bennell 1986). Liquefaction is very sensitive to the actual state of the granular soil, especially its relative density, void ratio, mineralogy, grain size distribution, particle shape and over-consolidation ratio (OCR). However, undisturbed sampling of granular soils is difficult and often not possible. Avoiding the sample disturbance is one great advantage of *in-situ* testing and it is therefore an important alternative to traditional sampling and laboratory testing. Since quasi-static cone penetration tests do not impose cyclic loads on the soil, the analysis of liquefaction potential from classic CPTu is always indirect and subject to certain assumptions (e.g., Robertson and Fear 1997). To evaluate cyclic behavior of marine soils directly from *in-situ* tests,

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cyclic loads are imposed directly *in-situ* with the use of the piezovibrocone.

The vibrocone was first introduced by Sasaki *et al*. (1984). This instrument induced cyclic loads while measuring dynamic tip resistance. Tokimatsu (1988) described the work of Sasaki *et al*. (1984) in utilizating vibrocone test at two locations in sands. Historically, at one of the locations, extensive ground settlement occurred due to liquefaction during an earthquake event while at the other location no settlement occurred during the same earthquake. The vibrocone apparatus that Sasaki *et al*. (1984) utilized had a cross sectional area of 15 cm^2 i.e., larger in diameter than standard 10 cm^2 cone penetrometers. In their apparatus, a built-in vibrator induced horizontal vibration with a frequency of 200 Hz. Their vibrocone measurements at a location with a history of liquefaction during the earthquake gave dramatically lower vibratory tip resistance than static tip resistance, while at a location with no liquefaction, static and vibratory tip resistance were almost identical. To directly compare static and vibratory tip resistances, Sasaki *et al*. (1984) proposed the reduction ratio (*RR*):

$$RR = 1 - \frac{q_{cv}}{q_{cs}} \quad (1)$$

where, q_{cv} is the vibratory cone penetration resistance and q_{cs} is the static cone penetration resistance. Values of *RR* near unity indicate small measured values of q_{cv} compared with q_{cs}, equal values of q_{cs} and q_{cv} give an *RR* value of zero (Bonita *et al*. 2004). Tokimatsu (1988) defined sediments with *RR* values of more than 0.80 as having high liquefaction potential. The term vibrocone changed to piezovibrocone after installation of a pore pressure sensor on the cones and measurements of vibratory pore pressure while inducing cyclic loads. Mitchell (1988) used a piezovibrocone with frequency of 200 Hz, in a saturated sand layer. Under the effect of vibration, the pore water pressure of sandy soil, measured from u_2 position port, increased near the cone and simultaneously the tip resistance decreased. This is in agreement with the expected behavior of soil during liquefaction; cyclic loading leads to compaction of the grain skeleton, which results in excess pore pressure. This then leads to a reduction of the effective stress until the effective stress and the stress dependent shear strength approach zero in the liquefied soil. At the University of British Columbia, Moore (1987) tested a piezovibrocone with 75 Hz frequency in a silt which resulted in a reduction of tip resistance without evidence of change in excess pore pressure detected by a pressure transducer shoulder element. In 1999, Wise *et al*. developed a piezovibrocone and recorded the response of tip and pore water pressure to vertical impulses of 5 Hz in liquefiable sands. The results show a significant spike in the pore water pressure measured from u_2 position port, in response to dynamic vibratory forces. He suggested that the area in which the pore water pressure spike was observed is a zone susceptible to liquefaction. Five years later in 2004, smaller scale vibratory cone penetration based tests were conducted by Bonita *et al*. in a laboratory setting to measure, evaluate and quantify the influences of vibration on the penetration resistance and pore water pressure values under a vertical force with vibration frequencies ranging from 5 Hz to 135 Hz. Their results indicated that elevated pore water pressure generated due to vibration of the CPTu cone was not detected by sensors (u_1 and u_2) within the instrument. However, elevated pore water pressures were measured by pressure gauges in the soil mass 0.35 m away from the cone penetrometer. They also observed that the penetration resistance values can be dramatically reduced if the volume of undrained soil encompasses the zone of influence of the cone penetrometer. The authors concluded that the increase in pore water pressure resulted in the effective stresses being at or near liquefaction conditions within the influence zone of the cone. Recently, Samui and Sitharam (2010) published details on the development of a hydraulically

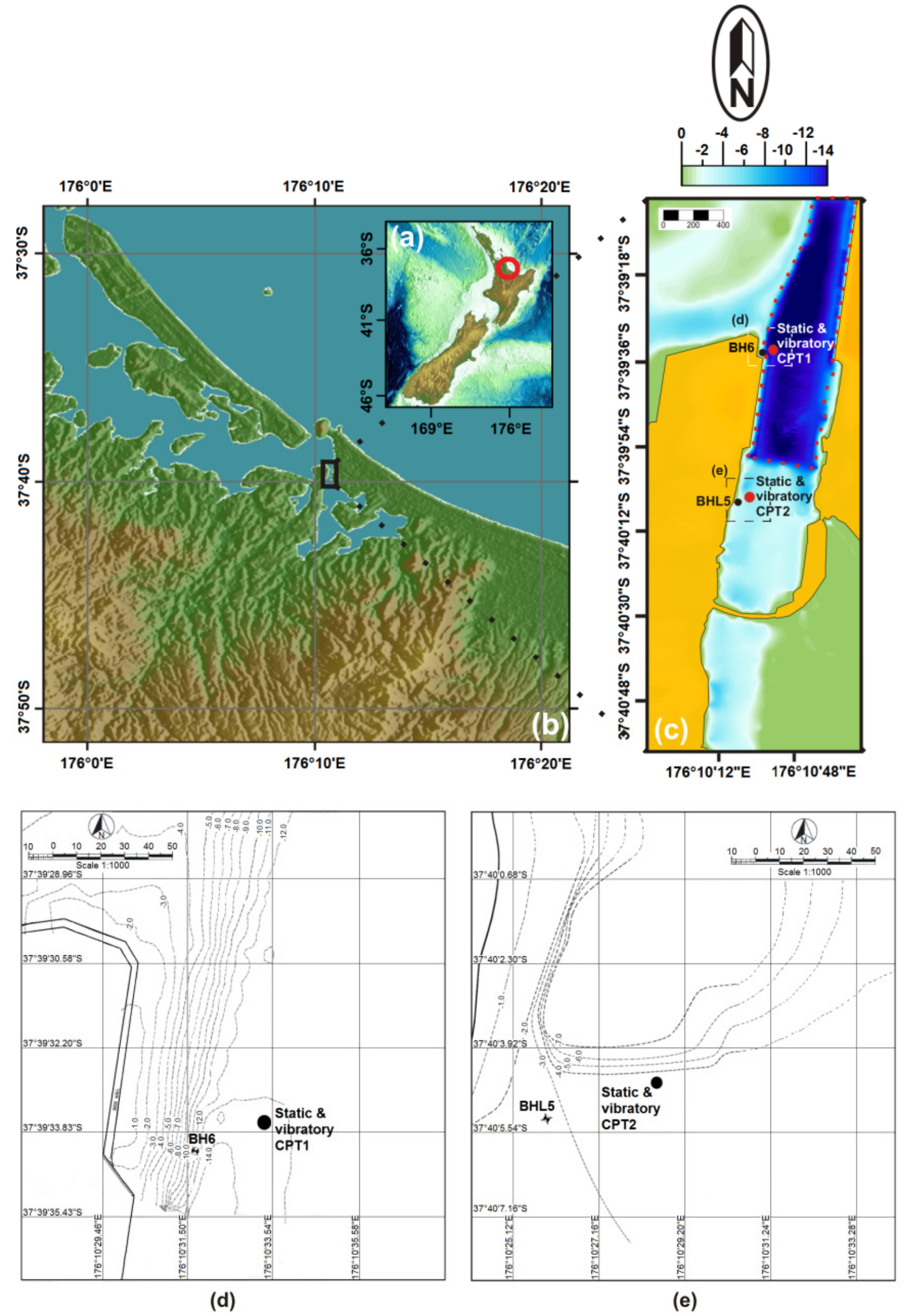

Fig. 1 (a) Map of New Zealand; (b) Bay of Plenty; and (c) bathymetry map of southern Tauranga Harbor with static and vibratory piezocone locations. In map c, dredging boundary is marked by a red dotted line. Locations of the boreholes which are selected to interpret sediment stratigraphy near the locations of static CPTu and vibratory CPTu at; (d) Sulphur Point Northern Wharf Extension (after OPUS (2011)); and (e) Sulphur Point Southern Wharf Extension. Except map (d), all maps are generated from the Land Information New Zealand (LINZ) data. In map c, d and e, all depths are set relative to the lowest astronomical tide driven laboratory piezovibrocone and calibration chamber unit, but no further test results.

GeoLogismiki, in collaboration with Gregg Drilling Inc. and Prof. Peter Robertson have developed software called CLiq (2008). The software uses static CPTu results to predict the likelihood of sediment liquefaction. For liquefaction assessments, the software applies the state of the art National Center for Earthquake Engineering Research (NCEER) method (Youd and Idriss 2001) and also includes the latest assessment procedure developed by Robertson (2009).

Vibrocones and piezovibrocones have so far only been utilized in laboratory or *in-situ* on onshore sediments, but not offshore. In the offshore realm, many hazards and risks are associated with liquefaction such as earthquakes triggering submarine landslides or the liquefaction of soil beneath pipelines. In this paper, we focus on the effect of vibration on coastal near shore sediments presenting two pairs of static CPTu and vibratory CPTu deployed in Tauranga Harbor, New Zealand. In the second step, the piezovibrocone data are compared with the results of standard static CPTu based liquefaction.

2. Testing locations and site characterization

Measurements were undertaken in two separate locations, one in a dredged and one in an undredged area of Tauranga Harbor, Bay of Plenty, New Zealand (Fig. 1). The major dredging operations were performed in 1992 along the shipping channel in the Tauranga Harbor and deepened the harbor channel to ~13 m (Healy *et al*. 1996). Since then, due to sediment dynamics at the harbor, there have been several other smaller dredging operations to maintain the shipping channel depth. Sediments in the Tauranga area consist of Pliocene to Pleistocene rhyolitic volcanoclastic material derived predominantly from the Taupo Volcanic Zone (Briggs *et al*. 2005) and marine sediments. Within the upper few tens of meters of sediments at the Tauranga Harbor, five general lithofacies were identified by Davis and Healy (1993). In descending order, the lithofacies are shelly sand, shelly mud, undifferentiated sand, undifferentiated mud and pumiceous facies.

3. Methods

New CPTu data and existing core descriptions are utilized for this study (Table 1).

Table 1 CPTu and borehole descriptions used for this study

Site	Coordinate		Reference	Depth (m)	Water depth (m)
Static CPTu1	37° 39' 33.02" S	176° 10' 35.16" E	GOST, Feb/March 2012	13.10	12.50
Vibratory CPTu1	37° 39' 32.97" S	176° 10' 35.23" E	GOST, Feb/March 2012	13.10	
BH6	37° 39' 34.00" S	176° 10' 31.58" E	OPUS, 2011	63.15	11.50
Static CPTu2	37° 40' 04.77" S	176° 10' 28.23" E	GOST, Feb/March 2012	3.50	2.30
Vibratory CPTu2	37° 40' 05.07" S	176° 10' 28.54" E	GOST, Feb/March 2012	3.50	
BHL5	37° 40' 05.72" S	176° 10' 25.90" E	Port of Tauranga, 2000	38.00	2.80

3.1 In-situ CPTu

In February 2012, a field investigation was undertaken in collaboration between the University of Bremen, the University of Waikato and the Port of Tauranga. During four weeks of operation, a series of CPTu soundings were performed at the Tauranga Harbor Stella Passage and entrance channel. Of these, two static CPTu and two vibratory CPTu were selected for this study (Fig. 1(c)). The two vibratory CPTu's (Fig. 1(c)) are the only vibratory tests which were deployed during the 2012 field investigation at Tauranga Harbor, and only two static CPTu were conducted in the vicinity of the vibratory CPTu at both sites for comparison purposes. Other static CPTu were not utilized in this study due to: (i) considerable distance from both sites; and (ii) only two vibratory CPTu results are available for comparisons with the static CPTu results.

Static CPTu and vibratory CPTu measurements were conducted using the Geotechnical Offshore Seabed Tool (GOST) (Fig. 2). The GOST was developed at the MARUM - Center for Marine and Environmental Sciences, the University of Bremen. The instrument design and modes of deployment are described comprehensively by Jorat *et al*. (2014). Operations in Tauranga Harbor were undertaken from a harbor barge positioned by a tugboat, with the CPTu frame lowered and retrieved from the seafloor using a mobile crane mounted on the barge. The GOST system was deployed directly below the barge. Platform equipment and tools were kindly shared by the Port of Tauranga authorities. Distances between static and vibratory soundings are 3 m for CPTu1 and 10 m for CPTu2. These distances were obtained from a DGPS device mounted on the barge during each deployment. To maximize positioning accuracy, an on-barge DGPS unit was positioned directly adjacent to where the GOST was deployed. We know that water currents would cause a level of error in the recorded locations for each test, however this was unavoidable as we were logistically restricted to an on-barge DGPS unit. Nevertheless, due to the shallow seabed and the significant weight of the instrument, errors in positioning appear negligible. In CPTu1, after

Fig. 2 The Geotechnical offshore seabed tool during deployment in Stella Passage, Tauranga Harbor

the static test, the GOST was lifted, the barge was repositioned with the anchor-winches allowing sufficient distance and the GOST was deployed again for the vibratory test. In the CPTu2, the vibratory test was conducted approximately 24 hours after the static test and the barge was repositioned using the static test DGPS position. Since the vibratory CPTu1 was deployed immediately after the static test deployment, tidal differences between the static and vibratory tests were insignificant. For CPTu2, as the vibratory test was conducted nearly 24 hours after the static test, no major tidal differences between static and vibratory tests were observed.

In general, vibrators consisting of a horizontally rotating mass tend to create gaps between the penetrometer and the soil; these gaps influence the recorded penetration resistance values (Bonita *et al.* 2004). To avoid this issue, the 5 cm^2 cone in the GOST is designed to generate vertical excitations while conducting vibratory CPTu. To generate vibration during each push motion, GOST speed regulators enforce sinusoidal speed variations which generate vibration during penetration. For the vibratory CPTu measurements in this study, the cone vibrated with frequency of 2.5 Hz and amplitude of 0.62 mm.

As mentioned in the introduction, tip resistance and pore water pressure results have mainly been used and recommended by other researchers to compare geotechnical properties of sediments subjected to dynamic loadings. Accordingly, in this study, tip resistance and pore water pressure from static and vibratory CPTu were utilized for comparisons and the results of sleeve friction are not reported in this manuscript.

To calculate relative density (D_r) from static CPTu results Juang *et al.* (1996) proposed

$$D_r^2 = \left(\frac{1}{Q_F}\right)\left[\frac{\left(\frac{q_c}{p_a}\right)}{\left(\frac{\sigma'_v}{p_a}\right)^{0.5}}\right] \tag{2}$$

where, q_c = cone tip resistance; p_a = atmospheric pressure (about 100 kPa); σ'_v = effective vertical stress and Q_F = an empirical constant of the least-square regression. Juang *et al.* (1996) suggested that the use of 0.5 for σ'_v /p_a is sufficiently accurate. They also recommended value of 332 for sands of low compressibility.

3.2 Core descriptions

A significant number of exploration boreholes have been drilled in conjunction with the development of Tauranga Harbor since 1948. Among those, the two borehole descriptions closest to the locations of static CPTu and vibratory CPTu in dredged and undredged sections were selected to interpret sediment stratigraphy (Figs. 1(d) and (e)). BH6 and BHL5 used in this study were taken and described by different companies as specified in Table 1. Several other cores have been drilled in the area, but these are at a considerable distance from the test sites and not used in this study. Due to the time passed since the holes were drilled, most of the core material has been lost. Furthermore, the borehole descriptions were performed by different operators using a variety of description protocols. BH6 was collected using a Morooka rotary drilling rig with wireline triple tube coring with a diameter of 63.50 mm (OPUS 2011). The recovery percent in BH6 is 91% (OPUS 2011). Unfortunately, except the core coordinates and description, no further information is available for BHL5.

For BH6, OPUS (2011) reported the results of a consolidated undrained triaxial compression, a hydrometer and three wet sieve particle size analysis tests conducted on samples from different depth intervals of the core.

3.3 Liquefaction potential evaluation by piezovibrocone

In this study, reduction ratio values are the basis for determination of liquefiable and non-liquefiable zones. As recommended by Tokimatsu (1988), sediments with reduction ratio values of more than 0.80 are considered liquefiable.

3.4 Liquefaction potential evaluation by CLiq software

In order to evaluate liquefaction potential, Cyclic Stress Ratio (*CSR*) and Cyclic Resistance Ratio (*CRR*) parameters have to be specified as explained e.g., in Kreiter *et al*. (2010).

In the CLiq software, Cyclic Stress Ratio is calculated following Seed and Idriss (1971), and the Cyclic Resistance Ratio is calculated following Robertson (2009). Using Cyclic Stress Ratio and Cyclic Resistance Ratio values, the factor of safety against liquefaction (FS_{liq}) is computed by the software as:

$$FS_{liq}(CRR / CSR)MSF \tag{3}$$

where, *MSF* is a magnitude scaling factor described by Youd and Idriss (2001) as,

$$MSF = \left(\frac{M_w}{7.5}\right)^{(-3.3)} \tag{4}$$

where, M_w is the earthquake moment magnitude. The Darfield moment magnitude (M_w) 7.1 earthquake of September 2010 (Gledhill *et al*. 2010) was one of the most recent earthquakes which has struck New Zealand, causing considerable damage and generating major liquefaction in liquefiable soils. Therefore, we use, M_w = 7.1, as a real case earthquake moment magnitude value for this study to evaluate the liquefaction potential of soil based on CLiq software.

4. Results

4.1 Static and vibratory CPTu1

The CPTu traces at site CPTu1 are consistent with the description of BH6 allowing for slight variations in the thickness of the layers (Fig. 3(a)). Static and vibratory tip resistances, down the profile, are identical except at the gravel ignimbrite layer at 10.50 m and where vibratory tip resistance is lower than static tip resistance (Fig. 3(b)). The vibratory pore water pressure of silts and clays, pumiceous sand and pumiceous sands and silts with gravel layers is significantly lower than those measured in static mode (Fig. 3(c)).

Sediments in the Tauranga area consist of Pliocene to Pleistocene rhyolitic volcanoclastic material derived predominantly from the Taupo Volcanic Zone (Briggs *et al*. 2005) deposited in different sequences across the Tauranga region. Apparently, sediments of each sequence might be subjected to changes in physical and mechanical properties due to factors such as erosion and/or weathering. However, since the static and vibratory test locations are only 3 m away from each

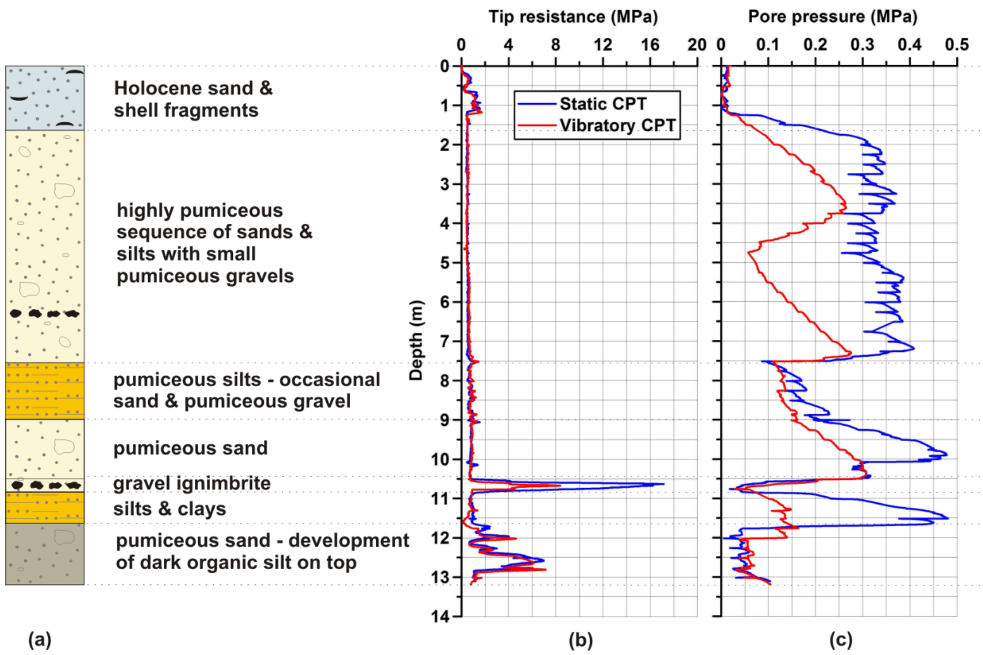

Fig. 3 (a) Sediment stratigraphy at the location of BH6. Static and vibratory CPTu1 measurements of (b) tip resistance and (c) pore water pressure

other and both locations have very similar environmental conditions (i.e., moisture, temperature and chemical components), sediment properties in both sites are believed to be consistent such that changes in vibratory tip resistance occurred due to vibration of the cone and not changes in sediment properties or grain size.

The CPTu based relative density values for materials from the Holocene sand and shell unit is between 1.7 and 21.9% which is considered as very loose/loose compactness. However, the relative density of the gravel ignimbrite layer is between 25.4 and 71.9% which is considered as loose/dense compactness. The relative density values for materials from the pumiceous sand units are between 10.9 and 21.7% which equate to very loose/loose compactness. A sieve particle size analysis test reported by OPUS (2011) was conducted on samples belonging to pumiceous sand and silt unit at the depth of 7 m. From this test D_{50} = 0.28 mm.

The reduction ratio profile shows a low potential for liquefaction for the tested soil (Fig. 4(a)). The factor of safety against liquefication derived from the static CPTu predominantly indicates no likelihood of liquefaction for the tested soil (Fig. 4(b)). However, factor of safety values are slightly lower between depths of 3.80 m and 5 m and at the depth of 7.40 m suggesting that "liquefaction and no-liquefaction are equally likely" for these sediments. At 10.50 m, there is a slight fall of factor of safety consistent with the reduction ratio profile, but still in the "unlikely to liquefy" field.

4.2 Static and vibratory CPTu2

The CPTu traces at site CPTu2 are consistent with the description of BHL5 (Fig. 5(a)). At the top of the Holocene sand and shell fragments layer and in the silts layer with vegetation and shell

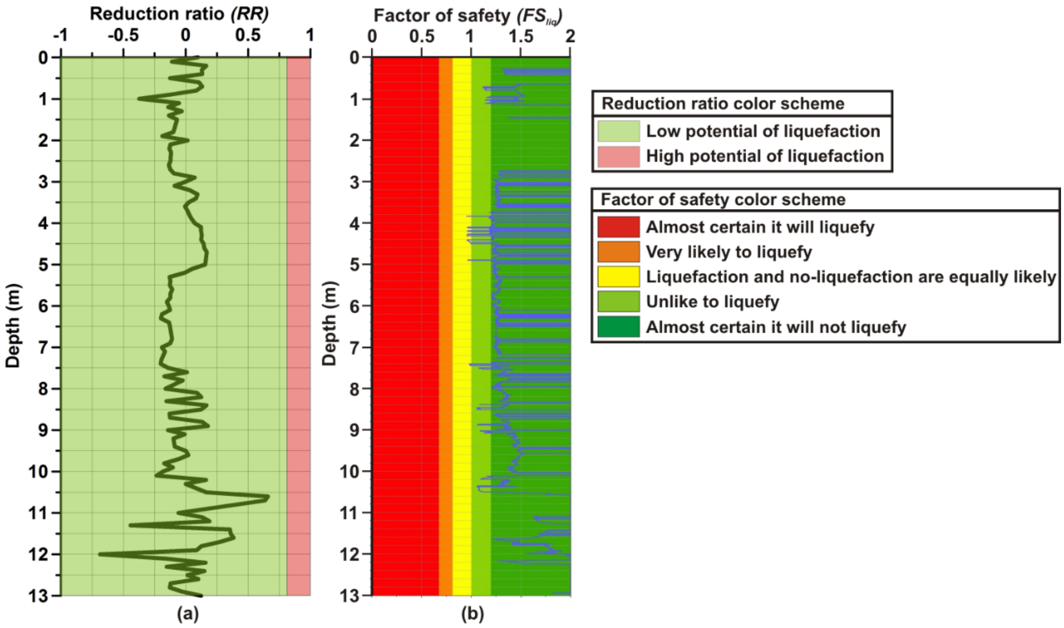

Fig. 4 (a) Reduction ratio derived from static and vibratory CPTu1 tip resistance results. High (> 0.80) and low potential (< 0.80) areas for liquefaction are denoted following Tokimatsu (1988); (b) Factor of safety against liquefaction calculated by CLiq software based on static CPTu1 results

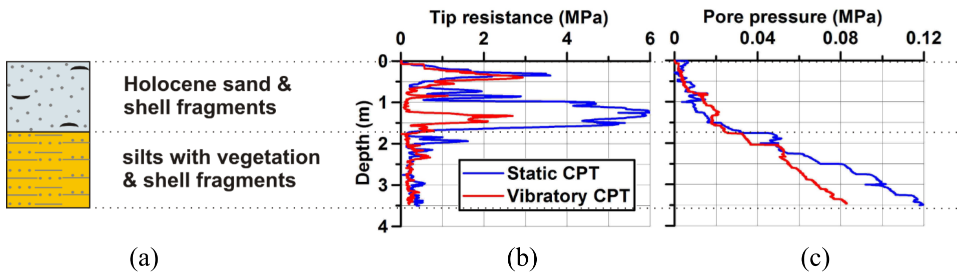

Fig. 5 (a) Sediment stratigraphy at the location of BHL5. Static and vibratory CPTu2; (b) tip resistance; and (c) pore water pressure

fragments, the static and vibratory tip resistances have similar values. Between 0.60 m and 1.70 m depths, vibratory tip resistance is considerably lower than the static tip resistance (Fig. 5(b)). Static and vibratory pore pressure of the Holocene sand and shell fragments layer are equal, however in the silts with vegetation and shell fragments layer, the vibratory pore pressure decreases consistently with increasing depth (Fig. 5(c)).

The CPTu based relative density values for materials from the Holocene sand and shell unit are between 6.4 and 42.9% which is considered as loose/medium compactness.

The reduction ratio profile shows a high liquefaction potential between depths of 1 m and 1.30 m, while the rest of the profile indicates a low potential of liquefaction (Fig. 6(a)). In contrast, the profile of factor of safety against liquefaction indicates no likelihood of liquefaction at all (Fig. 6(b)).

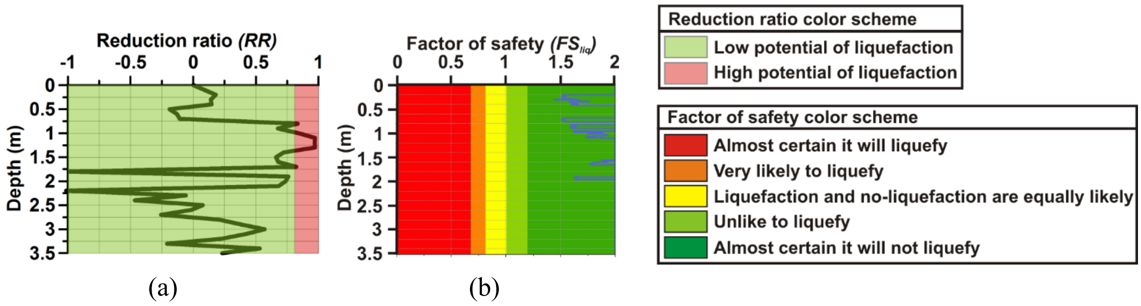

Fig. 6 (a) Reduction ratio derived from static CPTu2 and vibratory CPTu2 tip resistance results. High (> 0.80) and low (< 0.80) potential areas for liquefaction are denoted following Tokimatsu (1988). (b) Factor of safety against liquefaction calculated by CLiq software based on static CPTu2 results

5. Discussion

5.1 Static and vibratory CPTu1

The significant reduction of vibratory tip resistance in the gravel ignimbrite layer of CPTu1 is consistent with other studies (e.g., Sasaki *et al*. 1984). The reduction of vibratory tip resistance was not sufficient to generate liquefaction (Fig. 4(a)) and the factor of safety against liquefaction from static analysis matches the reduction ratio results. Hence, the gravel ignimbrite reacts to cyclic loading but it is not liquefiable. The equal static and vibratory tip resistances in the rest of the profile indicate that the reduction of vibratory tip resistance is not artificial and only occurs in materials vulnerable to dynamic loading.

In contrast to the expectation from liquefaction theory, the static and vibratory pore water pressures in the gravel ignimbrite layer are equal, indicating no liquefaction potential. A similar tip resistance and pore water pressure response was observed by Bonita *et al*. (2004) in sand and it is possible that a similar mechanism took place in the gravel ignimbrite layer. Bonita *et al*. (2004) indicated that pore water pressure sensors mounted on the CPTu cone (u_1 and u_2) could not detect elevated pore water pressure generated due to vibration of the CPTu cone within the instrument, however, 0.35 m away from the cone penetrometer, elevated pore water pressures were measured with pressure gauges.

We understand that results obtained in the gravel ignimbrite in this study cannot be directly compared with results obtained in sand by Bonita *et al*. (2004). However, we suspect that the similar static and vibratory pore water pressure response in sand implies that a similar mechanism occurred in the gravel ignimbrite of this study which resulted in the static and vibratory pore water pressure recorded by the CPTu cone being equal. Alternatively, a reduction of vibratory tip resistance may have occurred due to the tip of the instrument hitting different particle sizes (e.g., heterogeneities in the gravel).

While vibration did not have any influence on the tip resistance of the pumiceous layers, vibratory pore pressure is lower than the static pore pressure. Marks *et al*. (1998) conducted cyclic triaxial tests on loose pumiceous sand samples (Puni pumice sand) taken from the Puni river approximately 150 km north-west of CPTu1 and CPTu2 locations. Puni pumice sand derived predominantly from the Taupo Volcanic Zone as well, however, small volcanic cones in the

Auckland region may introduce a portion to the Puni sand. Marks *et al*. (1998) observed a rise in excess pore pressure during the tests which indicates that pore pressure in pumiceous sand may increase under the influence of dynamic loading. Similar to the observations in the gravel ignimbrite and the results of Bonita *et al*. (2004), it is believed that the reduced vibratory pore water pressure values recorded by the cone in this study in the pumiceous layers are an artifact. Possibly, the pore water pressure increases with distance from the pore pressure port. However, since the vibratory tip resistance is not reduced, there is no liquefaction potential. Marks *et al*. (1998) reported relative density values of two loose pumiceous sand samples as 32 and 35% which is measured as loose compactness. A very loose/loose compactness state of pumiceous sand layers in this study is similar to the compactness state of Puni sand, implying similar relative density conditions. Alternatively, D_{50} = 0.28 mm of the pumiceous sand and silt layer is lower compared to D_{50} = 0.76 mm of the Puni pumiceous sand. This likely occurs due to the presence of silt in the pumiceous unit of this study. Marks *et al*.'s (1998) work on Puni pumice sand is explained and compared here to indicate that the pore water pressure in the pumiceous layers of this study may increase under the influence of dynamic loading. However, this does not mean that if Puni pumice sand liquefies, pumiceous layers in Tauranga Harbor must also liquefy.

5.2 Static and vibratory CPTu2

The reduction ratio of the lower part of the Holocene sand and shell fragments layer indicates a high potential of liquefaction after the method of Sasaki *et al*. (1984). At the same depth, there is only a slight rise of vibratory pore water pressure. This is similar to the static and vibratory pore pressure response observed in the sand layer by Bonita *et al*. (2004) (Fig. 3). The same layer appears not to be liquefiable based on classic static CPTu analysis and, therefore, we suggest that static methods were not able to identify the zone with a high potential of liquefaction and have erred on the unsafe side. This is probably due to the fact that the reaction to cyclic loading is only empirically linked to the reaction of static loading and an empirical method is only valid for the range of soil types included during development of the technique. Yet, offset between two CPTu holes and potential local heterogeneity may affect the reduction ratio. Usually, reducing offset between static and vibratory soundings lowers heterogeneity. In the onshore realm, minimizing this offset is much easier than in the offshore realm due to factors such as current and other positioning problems.

In the lower part of CPTu2, in the silt with vegetation and shell fragments, there is no vibratory tip resistance reduction and again there is a reduction in vibratory pore water pressure. A cyclic triaxial test on sea silt also found an increase in pore water pressure (Konrad 1985). Therefore, the vibratory pore water pressure again differs to the expectation from triaxial test results, similar to the observations made by Bonita *et al*. (2004).

The vibratory pore water pressure is showing no evidence of liquefaction in all tested lithologies, but conversely in many cases is lower than would be expected from cyclic triaxial tests on comparable materials (Marks *et al*. 1998, Konrad 1985). Triaxial tests are element tests with one and the same stress state in the whole sample. CPTu, in contrast, induces a complex material-dependent stress field in the tested soil (e.g., Ahmadi *et al*. 2005), hence stress and strain changes adjacent to the cone during penetration may cause unexpected pore pressures especially in a complex non-linear material such as soil. The proposed explanation, that the shear stress adjacent to the cone is causing lower than expected pore pressure, is similar to the former speculation (Bonita *et al*. 2004). The position of the pore pressure port in u_2 position (Lunne *et al*. 1997) behind the conical part of the probe may also help to explain the measured pore pressure values. It is likely that a pore pressure measurement in u_1 position directly at the tip would give a signal consistent with the cyclic triaxial tests because the loading has a normal component, while behind the cone there is only movement parallel to the soil-steel interface. In addition, vertical dissipation of the excess pore pressure may play a role, since the rod is 5.20 mm thinner than the probe and there is probably an annular gap around the rod allowing for free drainage. However, since the rod geometry in the vibratory test was similar to the one in static test and the distance between the cone tapering and the pore pressure port is 291.80 mm, corresponding to more than 11 d (d = diameter of the cone), conform to ISO 22476-1:2013-10 standard, vertical dissipation of excess pore pressure due to geometry of the cone and the rod seems unlikely. Nevertheless, the vibration may allow for enhanced vertical upward dissipation of excess pore pressure along the CPTu probe and this may explain the unexpected low pore pressure readings. In summary, elevated pore water pressure under the influence of vibration in vibratory CPTu cannot be measured by pore pressure sensors mounted on the GOST CPTu cone. However, evidence from other studies verifies that pore water pressure indeed increases in soil which causes liquefaction of potentially liquefiable layers.

6. Conclusions

Piezovibrocone tests were performed in volcanoclastic and marine sediments at Tauranga Harbor and the results are compared to static CPTu based liquefaction analysis.

In this study, two sets of static and vibratory offshore CPTu were utilized. As the piezovibrocone technique has rarely been used *in-situ* and our results are the first series of reported *in-situ* piezovibrocone tests conducted in the offshore realm, here we demonstrate utilization of the piezovibrocone technique for offshore soils. Next, we touch on the subject of liquefaction analysis of offshore soils by using peizovibrocone and discuss our results.

Piezovibrocone has proven superior to static CPTu based methods for liquefaction analysis by measuring the reaction to actual cyclic loading and not being an empirical method, however artefacts may be introduced by local heterogeneities.

Two liquefaction-vulnerable layers are identified: one slightly vulnerable ignimbrite; and one clearly vulnerable marine sand. The liquefaction-vulnerability of the sand is not detected by the static CPTu based liquefaction analysis, an error on the unsafe side.

The vibratory pore water pressure is consistently lower than or equal with the static one, this is opposite to the expectations from liquefaction theory and cyclic triaxial tests on similar materials. This is believed to be an artefact and has been observed before in the literature and the possible causes are discussed.

At this stage, the piezovibrocone technique is not able to recognize differences between liquefaction properties of dredged and undredged sites considering soils' OCR. To address this matter, core samples have to be taken and extensive geotechnical laboratory tests are required.

In summary, measuring the reduction in vibratory tip resistance in offshore *in-situ* piezovibrocone tests in marine sediments is shown to be an effective method for identifying potentially liquefiable sediment layers. By using the *in-situ* piezovibrocone testing technique for offshore site investigations, considerable time and money may be saved. However, since the offshore realm is a new era for piezovibrocone tests, additional testing analysis is needed to properly test the concept and assess its use in commercial works.

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