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Site characterization for liquefaction assessment of gravelly reclamations at CentrePort, Wellington

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ABSTRACT: The 2016 M_w7.8 Kaikoura earthquake caused widespread liquefaction in CentrePort, Wellington, which produced substantial lateral ground movements along with global and differential settlements. Following the earthquake, three phases of subsurface exploration were launched to investigate the thick end-dumped gravelly fills and hydraulically-placed dredged reclamations. Fieldwork included 121 CPTs and several shear wave velocity profiles, which are utilized to develop detailed subsurface soil profiles for the reclamations at the port of Wellington. The spatial distribution, thicknesses, and depths of the end-dumped gravelly fills and sandy hydraulic fills are presented. Characteristic layers are identified, and representative CPT profiles from different reclamation zones are presented and discussed. The subsurface profiles distinguish between CPTs in areas of gravelly ejecta, silty-sand ejecta, and no liquefaction manifestation. Finally, recommendations are made on future work for this ongoing study.

1 INTRODUCTION

The port of Wellington (i.e. CentrePort) is a vital facility of economic significance at regional and national scales in New Zealand. The M_w7.8 2016 Kaikoura earthquake caused extensive liquefaction to the reclaimed soils at CentrePort, causing severe ground deformations, damage of wharves and buildings, and temporary close of operations. The reclamations are composed of gravel, sand and silt fractions. Hence, their liquefaction and associated damage were both of great interest. However, characterizing the gravelly fills is challenging. Immediately after the earthquake, an on-site reconnaissance documented in detail ground and structural damage. A comprehensive site exploration program was subsequently undertaken to characterize the subsurface conditions at CentrePort by means of cone penetration tests (CPTs) and shear wave velocity measurements. The first phase of this study presented observed damage and key results of initial 47 CPTs performed in 2017 (Cubrinovski et al. 2017a, 2018). This paper presents and discusses results from 74 additional CPTs used to enhance the site characterization. The combined CPT dataset is used to investigate the cyclic response of reclaimed soils. Key findings from the characterization of the reclamations and liquefaction assessment are discussed, including the development of representative CPT profiles for different reclamation zones. Insights from the ongoing program of research on gravelly and hydraulically placed reclamations are also shared.

2 SITE DESCRIPTION

Wellington, the capital of New Zealand, has a population of about 400,000 and is in the lower North Island. It was developed over the past 170 years after the European settlement in the 1850s. The original coastline from the 1850s is located approximately 200 m to 500 m inland from the current revetment line delineating a belt of reclaimed land that increases in width

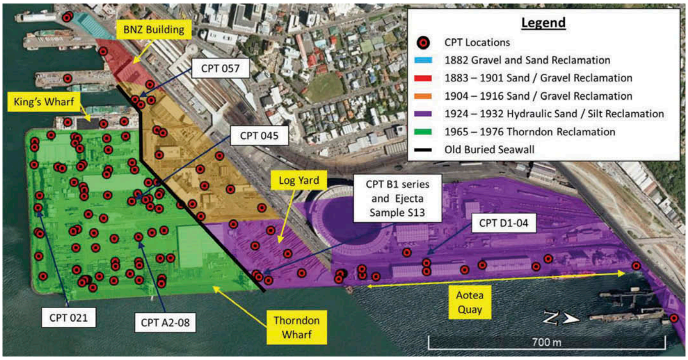

Figure 1. Aerial view of CentrePort showing the old buried seawall, reclamation zones indicating period of construction and soil materials used, locations of the 121 CPT locations utilized for this study, and the location of ejecta sample S13 (base image from Google Earth™).

towards the north along the waterfront and reaches its largest extent at CentrePort. The reclaimed land between the original coastline and the current revetment line consists of reclaimed soils of varying age, construction methods, and soil thicknesses. It presents a valuable case history involving several facets of great significance in the engineering assessment of liquefaction.

The various reclamations in the Wellington waterfront were constructed over three different periods. A large portion of the current port area was reclaimed in the final phase of construction between 1965 and 1976. This most recent reclamation is separated from the older reclaimed land by an old buried concrete seawall. An aerial view of CentrePort separating areas of different construction periods is illustrated in Figure 1. It also highlights the soils used for the reclamation and shows the location of the old buried seawall, which separates the end-dumped gravel-sand-silt fills from the hydraulic silty and sandy fills.

A significant portion of the CentrePort reclamations was developed using two methods of construction. The 1924-1932 reclamation (purple shading in Figure 1) consists of hydraulic fills constructed using dredged material (sandy and silty soils) from the original seabed in the vicinity of the reclamation works. The remaining reclamation was constructed by end-tipping of gravelly soils from nearby quarries using truck and barge operations.

The thickness of the fill increases with its horizontal distance from the original coastline (i.e. to the south). For the gravelly Thorndon Reclamation (green shading in Figure 1), the thickness increases from a minimum of about 10 m immediately south of the seawall to a maximum of approximately 22 m along the southern edge. The fills sit atop a thin layer of marine sediments of interbedded sand, clay and silty clay, which is overlying approximately 90-135 m of Wellington Alluvium composed of interbedded dense gravels and stiff silts. The top 3 m of the fill above the water table consist of a roller compacted layer underlain by relatively thick uncompact fills.

3 2016 KAIKOURA EARTHQUAKE GROUND MOTION

The M_w7.8 Kaikoura earthquake occurred on 14 November 2016 in the South Island of New Zealand. The complex rupture involving over 20 faults initiated at the southern end of the source zone and progressed northeast along the eastern coast of the South Island. The source-to-site distance (i.e. the closest distance between the causative faults and Wellington) was approximately 60 km (Cubrinovski et al. 2018). Ground motions were recorded at several strong motion stations in the vicinity of the port which included a rock site, natural soil deposits, shallow reclaimed sites, and deep reclaimed land sites in an area of rapidly changing geometry and depth to bedrock. The 2016 Kaikoura earthquake produced long duration of ground shaking with horizontal peak ground accelerations of about 0.25g (geomean of north-south and east-west components) at CentrePort. The recorded ground motions exhibited combined effects of site amplification (local soil conditions) and basin-edge effects. More details on the ground motions are provided in Bradley et al. (2018).

4 DETAILED SITE CHARACTERISATION

CentrePort reclamations were characterized using 47 CPTs and active and passive surface wave measurements using 114 seismic stations recording vibrations across the port during the first phase of the study in 2017 (Cubrinovski et al. 2018; Vantassel et al. 2018). This phase of the fieldwork incorporates data from 74 additional CPTs advanced in 2018.

Tests were performed with 10 cm^2 and 15 cm^2 A.P. van den Berg I-cones for the 121 CPTs. Field operations involved a predrill to a depth of approximately 3 m through asphalt pavement and dense compacted gravelly fill crust to increase total cone penetration depth. If early refusal was encountered during a test at depths less than approximately 10 m, CPT casing was extended beyond the refusal depth (Bray et al. 2014), and cone testing was then continued. The locations of all 121 CPT sites are shown in Figure 1.

Figure 2 shows six representative CPT profiles for sites of varying reclamation fill age, soil type and thickness. The locations of these six CPT sites are labelled in Figure 1. These profiles illustrate key features of different reclamation soil units, the underlying marine sediments, and the Wellington Alluvium as characterized by the CPTs. Traces of measured cone tip resistance (q_c) and soil behavior type index (I_c) based on Robertson (2016) are presented. One would normally correct the measured tip resistance for unbalanced water forces as recommended by Robertson (2016) to obtain q_t. However, due to the often erratic pore water pressure (u_2) measurements in the gravelly fill, q_c is used in this paper. Characteristic ranges (25th and 75th percentiles) for all soil units in each reclamation zone across the 121 CPTs are summarized in Table 1. Insufficient data were collected from the 1882 and 1893-1901 reclamation zones (Figure 1), so they are not included in this study.

CPT 045 represents a typical CPT profile for the 1965-1972 Thorndon Reclamation. The CPT trace shows 14 m of reclaimed end-dumped gravelly fill atop marine sediments and the Wellington alluvium. The reclamation fill is characterized by q_c values around 6 – 8 MPa and I_c values of approximately 1.9 – 2.3, which corresponds to sand/silt mixtures according to the Robertson (2016) classification scheme. Although sieve analyses indicated the liquefied material had 40% to 70% gravel-sized (> 4.75 mm) particles (Cubrinovski et al. 2017a), it appears that the finer sand-silt fractions of the gravelly soil reclamation primarily determined its

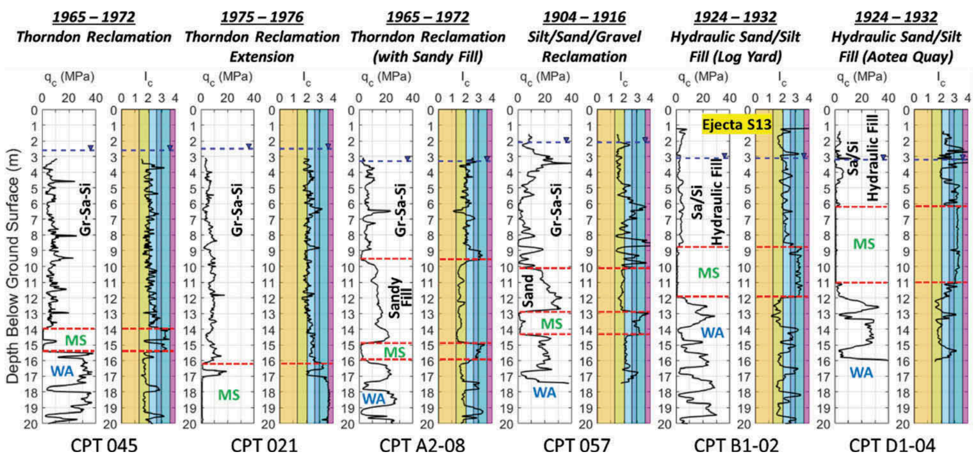

Figure 2. CPT tip resistance (q_c) and soil behavior type index (I_c) profiles for six sites representative of different reclamation zones. Gr-Sr-Si denotes the gravel-sand-silt reclamation, Sa/Si denotes sandy/silty soils in the hydraulic fills, MS denotes marine sediments, and WA denotes Wellington Alluvium.

Table 1. Characteristic q_c and I_c ranges (25th to 75th percentile) for reclaimed soil units based on all CPTs.

Soil Unit	1965 – 1976 Thorndon Reclamation	1924 – 1932 Hydraulic Fill	1904 – 1916 Reclamation
Gravel-Sand-Silt Fill	q_c = 6.3 – 7.8 MPa I_c = 2.06 – 2.19		q_c = 5.2 – 10.0 MPa I_c = 1.74 – 1.97
Sandy Zone in the Gravel-Sand-Silt Reclamation	q_c = 13.1 – 18.9 MPa I_c = 1.59 – 1.83		q_c = 16.6 – 22.5 MPa I_c = 1.61 – 1.76
Silty/Clayey Hydraulic Fill		q_c = 1.7 – 2.0 MPa I_c = 2.50 – 2.62	
Sand-Silt Hydraulic Fill		q_c = 3.7 – 4.7 MPa I_c = 1.98 – 2.08	
Marine Sediment	q_c = 1.3 – 2.0 MPa	I_c = 2.77 – 3.04	
Wellington Alluvium (Gravels)	q_c = 21.1 – 26.6 MPa	I_c = 1.81 – 1.91	
Wellington Alluvium (Silts)	q_c = 4.4 – 6.1 MPa	I_c = 2.77 – 3.04	

mechanical response during cone penetration. Examining this CPT profile closely, there are several spikes in q_c (for example at depths of 4.5 m and 8 m), which are associated with lower I_c values. The isolated spikes in q_c are not reflective of the overall response of the soil but are rather likely related to a sudden increase in soil resistance due to cone-interaction with gravel-sized particles and are indicative of the highly variable and complex composition of the gravel-sand-silt soil mixture.

CPT 021 represents a typical site in the 1975-1976 Thorndon Extension, which is the most recent reclamation of the port also composed of the gravel-sand-silt soil mixture. The q_c and I_c traces for the reclamation fill are similar to the 1965-1972 reclamation zone, but as mentioned previously, the thickness is greater and increases towards the south. Some CPT traces suggest the fill is as deep as 22 m (Cubrinovski et al. 2018).

CPT A2-08 represents one of the few areas in the 1965-1972 Thorndon Reclamation where a larger zone of sandy fill was identified in the gravel-sand-silt reclamation. The sandy fill is characterized by measured q_c values between 10 MPa and 20 MPa and I_c values between 1.6 and 1.8. The gravelly fill atop this pocket of sandy reclamation by and large showed similar q_c and I_c traces to those in the gravel-sand-silt mix units in other CPT profiles in this zone (e.g. CPT 045).

CPT 057 shows a typical profile for a site in the older 1904-1916 reclamation zone north of the buried seawall. This profile presents around 10 m of sand/silt fill with traces of gravels (as indicated by some spikes in q_c) atop sandy soil. In this area, the thickness of the fill is largest near the BNZ building located close by CPT 057 and decreases towards the log yard (Figure 1).

Typical CPT profiles in the hydraulic fill are represented by CPT B1-02 in the log yard and CPT D1-04 along Aotea Quay. Both profiles generally show low penetration resistances in the sand-silt fill up to depths of about 5 m to 10 m, overlying 3-5 m thick clayey marine sediments of very low tip resistance. The hydraulic fill primarily consists of two types of soils: sand-silt hydraulic fills, which are characterised by q_c traces around 4 MPa and I_c values around 2.0, and softer silts and clays exhibiting lower q_c values (< 2 MPa) and higher values of I_c (> 2.5) often exceeding I_c = 3.0. The thickness of the hydraulic fill layer generally decreased further north along Aotea Quay. Ejecta sample S13 was collected near CPT B1-02 following the 2016 Kaikoura earthquake, which indicates clearly the soil in this area liquefied (Cubrinovski et al. 2017a).

The marine sediments underlying the port fills are consistent throughout all the reclamation zones and are primarily soft, fine-grained soils, as indicated by the low cone resistance (q_c = 1.3 – 2.0 MPa) and high I_c values (2.8 – 3.0). This layer is typically around 1 m thick (shown in the CPT 045, and A2-08 and 057 profiles). The thickness of the marine sediments tends to increase as one progresses north along Aotea Quay, as illustrated by CPTs B1-02 and D1-04.

The CPT data indicate the Wellington alluvium consists of sand and gravel sublayers approximately 1.5 m thick, interbedded with stiff silty and clayey soils. The silty/clayey soils in the alluvium have low q_c values of around 3 MPa (I_c = 2.8 – 3.0) while the gravelly layers show q_c around 25 MPa (I_c = 1.8 – 1.9), exhibiting an increases penetration resistance.

5 OBSERVED LIQUEFACTION-INDUCED GROUND DEFORMATIONS

The 2016 Kaikoura earthquake triggered widespread liquefaction with non-uniform and scattered liquefaction ejecta on the surface pavement. Traces of ejected water, silt, sand and gravel with thicknesses of up to 150-200 mm were observed. Total deformation involved approximately 1 m of outward (seaward) movement of the reclamation slopes (edges) in unconfined directions, with development of liquefaction-induced lateral spread cracking and ground distress parallel to the edges progressing inland within the reclamation. Large vertical offsets up to half a meter were observed between pile-supported wharves and buildings and their surrounding ground. Further details of the vertical and lateral ground deformations, liquefaction manifestation, and associated damage to structures is provided in Cubrinovski et al. (2017a). Soil ejecta distribution and observed ground deformations in the eastern part of Thorndon Reclamation are shown in Figure 3.

6 REPRESENTATIVE SITES BASED ON LIQUEFACTION-MANIFESTATION

The grain-size distribution curves of ejecta samples collected near the CPT sites, and of other ejecta samples from different locations in the port, are presented in Figure 4 (Cubrinovski et al. 2017a). Sample S4 (purple curve) was collected near CPT 022, and it has 45% gravel content (or 67% for >2 mm criteria) and 4% fines content. The gravel and fines content for the remaining gravelly ejecta samples from the Thorndon Reclamation zone (grey curves) are in the range between 49% and 75%, and 1% and 8%, respectively. Sample S11 is a silty-sand ejecta collected near CPT A2-06 in the Thorndon Reclamation zone. Sample S13, which was collected near CPT B1-02, is a silty-sand ejecta sample from the 1924-1932 hydraulic fill reclamation zone.

The 121 CPT profiles are grouped into three categories based on the locations of the CPTs with respect to the observed liquefaction manifestation during the 2016 Kaikoura earthquake. The three categories are: (i) CPTs in areas of observed liquefaction manifestation of gravelly ejecta; (ii) CPTs in areas of observed silty-sand ejecta; and (iii) CPTs in areas of no observed liquefaction manifestation at the ground surface. Figure 5a and 5b shows some representative

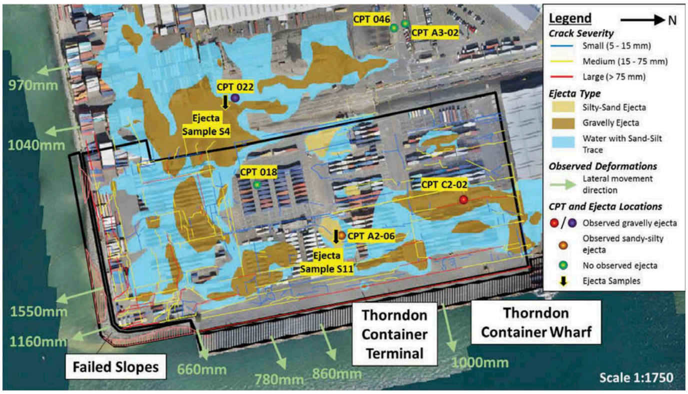

Figure 3. Map of Thorndon Reclamation highlighting lateral displacements, ground crack severity and liquefaction ejecta from aerial UAS survey (from CARDNO and drone video). Also shown are six CPTs and two ejecta samples (S4 and S11) collected after the 2016 Kaikoura earthquake (Cubrinovski et al. 2017).

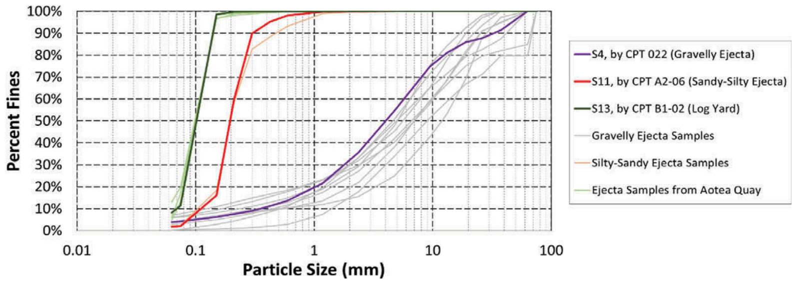

Figure 4. Grain-size distribution curves for three representative ejecta samples collected near CPT sites, and for ejecta samples from other locations around the port (Cubrinovski et al. 2017a).

CPT profiles from these liquefaction-manifestation categories at three locations with gravel-sand-silt fill in the 1965-1976 Thorndon Reclamation zone, and for three CPT locations in the same Thorndon Reclamation, but in a zone where sandy fill was encountered below the gravel-sand-silt fill.

Before comparatively examining the CPT-based results presented in Figure 5, it is important to recognize some response characteristics related to the temporal and spatial development of liquefaction in the reclamations and liquefaction manifestations at the ground surface. For example, one may anticipate some level of non-uniformity in the development of excess pore water pressures throughout the depth and laterally in the fill due to differences in materials, density, effective stress, and boundary conditions within the fill. In addition, cracks, fissures, and cavities created in the crust as a result of liquefaction below it are weaknesses that can be exploited as preferred pathways for groundwater flow and soil ejecta to reach the ground surface. Hence, non-uniformity in the manifestations of liquefaction are expected in liquefied ground. Furthermore, the absence of liquefaction manifestation at the ground surface does not eliminate the possibility of liquefaction actually occurring at some depth, but not manifesting at the ground surface. Caution is warranted when associating the observed liquefaction manifestation (or lack of it) to the soil profile characterized by a nearby CPT. With these caveats in mind, an attempt is presented herein to identify discernible differences in the soil profiles between the areas of ejecta (represented by CPTs C2-02, 022, and A2-06) and areas of no liquefaction manifestation (represented by CPTs A3-02, 046 and 018) in the Thorndon Reclamation. To facilitate the comparisons, simplified liquefaction triggering analysis was conducted using the Boulanger and Idriss (2014) CPT-based procedure, the results of which are presented in Figure 5 in terms of cyclic stress ratio (*CSR*) and cyclic resistance ratio (*CRR*) for the 2016 Kaikoura earthquake. The CPT q_c and I_c profiles and the results of simplified analyses were used to identify important soil profile characteristics with regard to liquefaction manifestation, such as the thickness of crust, thickness and vertical continuity of potentially liquefiable layers, and characteristic I_c values for critical layers with regard to liquefaction manifestation.

Of the three CPT sites in the gravel-sand-silt fill area, a representative CPT profile in an area where gravelly ejecta was observed is shown in CPT C2-02, and two representative CPT profiles where no liquefaction manifestation was observed is shown in CPTs A3-02 and 046. On the right of the I_c profiles, Figure 5a and 5b shows layers of potentially liquefiable (red in Figure 5) and potentially non-liquefiable (green in Figure 5) soils using an I_c threshold of 2.4. The criterion typically used to identify potentially liquefiable soils of $I_c < 2.6$ was reduced because there were silty soil layers with I_c between 2.4 and 2.6 as well as $I_c > 2.6$ which were less likely to manifest liquefaction based on the work of Cubrinovski et al. (2017b) among others. The I_c values for the potentially liquefiable gravel-sand-silt mixtures in these profiles are around 2.1 – 2.4. As discussed previously, it appears that the soil matrix and response to the cone penetration process of the gravelly fill is governed by the finer silty-sand fraction. These finer particles therefore control the measured cone penetration resistance for these CPTs and suggests the soil is susceptible to liquefaction. The results also show the *CRR* of the reclamation is well below the seismic demand imposed by the 2016 Kaikoura earthquake (i.e. the *CSR*).

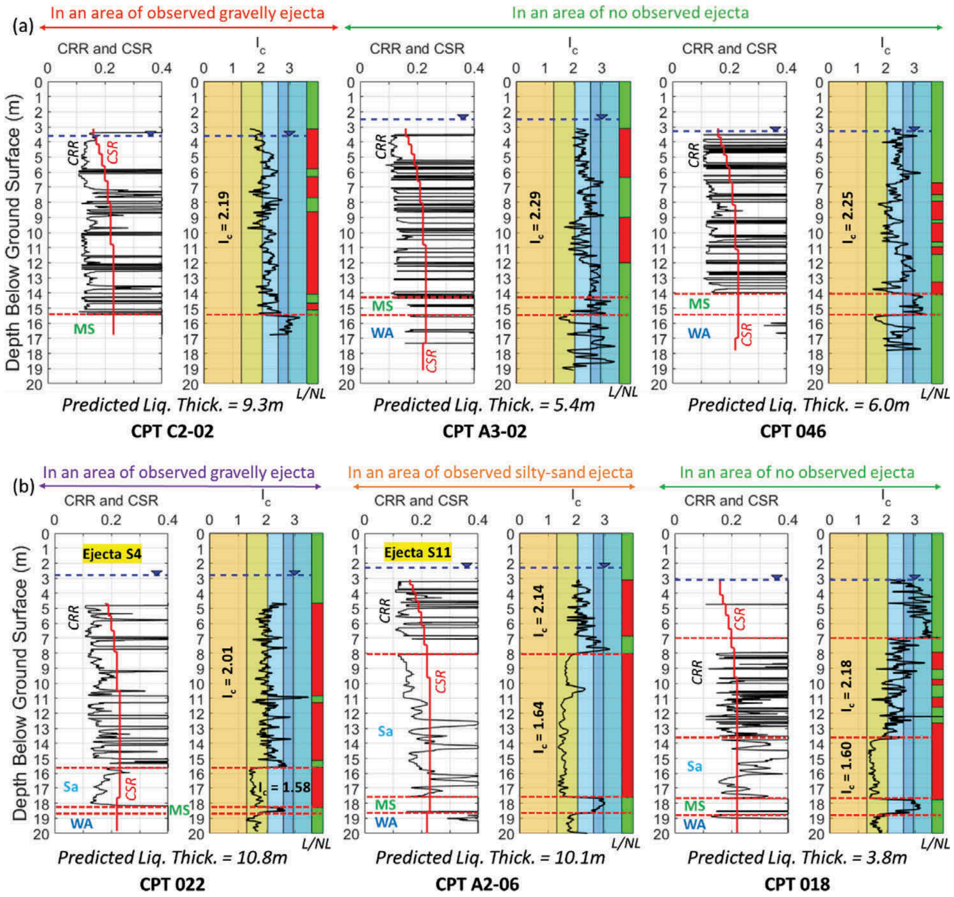

Figure 5. CPT cyclic resistance ratio (*CRR*), cyclic stress ratio (*CSR*) and soil behavior type index (I_c) profiles calculated using Boulanger and Idriss (2014) and Robertson (2016) for: (a) three sites consisting of gravel-sand-silt mix from the 1965-1976 Thorndon Reclamation; and (b) three sites with sandy reclamation below gravel-sand-silt fill from the 1965-1976 Thorndon Reclamation. The average I_c values for the cumulative layers of the fills predicted to liquefy (i.e. $CRR < CSR$) are given. To the right of the I_c profiles are approximate layers of potentially liquefiable soils (in red) and potentially non-liquefiable soils (in green). Gr-Sr-Si denotes the gravel-sand-silt reclamation, Sa denotes sandy reclamation, MS denotes marine sediments, and WA denotes Wellington Alluvium.

Despite liquefaction triggering being estimated in all three profiles, only CPT C2-02 was in an area of observed gravelly ejecta. CPT A3-02 and CPT 046 are located further west of CPT C2-02 and are 42 m and 35 m away from the nearest area of observed gravelly ejecta respectively. The traces of I_c around 2.4 are slightly higher than around I_c = 2.2 for C2-02, suggesting CPT A2-03 and 046 contain finer fractions in the soil matrix as opposed to C2-02. Furthermore, CPT C2-02 contains large continuous layers of liquefiable soils with a thick liquefiable layer from 8.6 m to 15.6 m. The calculated cumulative thickness of liquefied soils (i.e. thickness of $CRR < CSR$) is 10.8 m. In contrast, CPTs A3-02 and 046 contain smaller thicknesses of continuous liquefiable soils of about 3 m to 3.5 m, with the calculated cumulative liquefied thickness of 5.4 m and 6.0 m, respectively. Note that the lack of evidence of surface manifestation at these sites does not eliminate the possibility of liquefaction actually developing at some depths in the fill.

Of the three sites underlain by a pocket of sandy fill (Figure 5b), CPT 022 was in an area of observed gravelly ejecta, CPTA2-06 was in an area with silty-sand ejecta, and CPT 018 was in a location with no liquefaction manifestation. *CRR, CSR* and I_c profiles are shown along with layers of potentially liquefiable and non-liquefiable soils in Figure 5b.

At CPT 022, the sand fill is relatively deep at around 15.5 m depth. In comparison, the site within the area of observed silty-sand ejecta (A2-06) has much thicker sandy fill layers (9.5 m thick), which are also shallower (starts at 8 m depth). *CRR* values in the top 4 m of the sandy fill in A2-06 are consistently below the *CSR*, indicating that the shallowest part of this fill was relatively loose. This low density and relatively shallow depth of the weak sandy layer likely exacerbated the liquefaction manifestation with sandy ejecta at the ground surface. As $CRR < CSR$ for the gravel-sand-silt fills as well, it is probable that both the gravel-sand-silt layer and the sandy fill layer at CPT 022 liquefied, however, because of the large depth to the sandy fill and dominant gravel-sand-silt soils in the top 15 m, only the latter manifested at the ground surface.

CPT 018 is located far from the edges of the Thorndon Reclamations and 35 m away from the closest reported gravelly liquefaction ejecta. Although there are general similarities in the *CSR, CRR* and I_c traces for the gravel-sand-silt mix to the other CPTs in the gravelly reclamation, one important feature is that liquefiable soils are not encountered till 8 m depth. Very soft fine-grained silty-clayey soils, characterized by I_c values of around 3.3, are encountered below the water table from 3 m to 7 m depth. Another 3-4 m below this layer, from 8 m to 12 m depth, show that the gravel-sand-silt mix has I_c values close to 2.6, and layers of liquefiable soils are discontinuous over this depth range. Continuous liquefiable layers are encountered at large depths in the sandy fill, from 13 m to 17.5 m depth. These characteristics are consistent with the lack of liquefaction manifestation at the ground surface (Cubrinovski et al. 2017b). Areas of soil ejecta are characterized by vertically continuous liquefiable soils with low liquefaction resistance; whereas areas of no manifestation have thick crust or discontinuous liquefiable layers of smaller thickness.

7 CONCLUSIONS AND FUTURE WORK

The 2016 M_w7.8 Kaikoura earthquake caused widespread liquefaction leading to significant volumes of soil ejecta and permanent ground deformations in the end-dumped gravelly fills and hydraulic silty-sand fills at CentrePort in Wellington. Comprehensive CPTs performed at the port provide detailed characterization of the fills, and the underlying marine sediments and Wellington Alluvium. The soil behaviour type index I_c values imply soil behaviour typical for sand-silt mixtures rather than gravel-type behaviour implied by 40% to 70% gravel content in fills. CPT-based site characterisation also provided insights into the liquefaction manifestation during the 2016 Kaikoura earthquake. Thicker non-liquefiable crust or smaller thickness and lack of vertical continuity of liquefiable soils are encountered at sites that did not manifest liquefaction ejecta, as opposed to areas of massive soil ejecta that were characterized with vertically continuous approximately 10 m thick layers of low liquefaction resistance. Further studies will utilise the subsurface data to produce detailed CPT-based liquefaction assessment including post-liquefaction settlement estimates and share insights from advanced effective stress analyses.

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