13th Australia New Zealand Conference on Geomechanics – Acosta-Martínez & Lehane (Eds.)

Site characterisation and liquefaction assessment for the reclaimed soils in CentrePort, Wellington

R. Dhakal, M. Cubrinovski & C. de la Torre
University of Canterbury, Christchurch, New Zealand

J.D. Bray
University of California, Berkeley, California, USA

ABSTRACT: The 2016 M_w7.8 Kaikoura Earthquake caused widespread liquefaction in CentrePort, Wellington, resulting in substantial lateral movement along with global and differential settlements. The site is inherently complex to study due to the reclamations constructed with different soils (gravelly and sandy soils) of different ages (ranging from 40 to 100 years ago) and using different methods of construction. Therefore, CentrePort stands out as a unique case study when assessing its seismic performance. Liquefaction assessment of this reclamation poses many challenges due to its soil complexity and difficulty to obtain high-quality in situ data. Following the earthquake, two cycles of subsurface exploration program was launched investigating the thick end-dumped gravelly fills and hydraulically-placed dredged reclamations. 102 CPTs and various shear wave velocity profiles were successfully collected, and this study utilizes the data to produce 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 values presented. Results of CPT-based liquefaction triggering and post-liquefaction reconsolidation settlement assessments using state-of-the-practice procedures are discussed. The results are discussed in comparison with observed settlements and recommendations are made on future work for this ongoing study.

1 INTRODUCTION

The port of Wellington (i.e. CentrePort), New Zealand, is located in the central part of Wellington and is a vital facility that supports both regional and national economy of the city. The reclaimed soils at CentrePort have been subject to significant shaking due to recent seismic activity. The M_w7.8 2016 Kaikoura earthquake caused extensive liquefaction that led to severe ground deformations, damage to wharves and buildings, and temporary close of operations. After an on-site reconnaissance documenting observed ground and structural damage, a comprehensive site exploration program was performed to characterize the subsurface conditions at CentrePort by advancing Cone Penetration Tests (CPTs) and measuring shear wave velocity profiles. Previous literature on this study presented observed damage and key results of 47 CPTs performed in 2017 (Cubrinovski et al, 2017; 2018). This paper presents and discusses results from 55 additional CPTs to present an updated site characterization and use the overall CPT dataset for performing simplified liquefaction triggering analyses and associated damage indices for the 2016 earthquake. Key findings from the characterization of the reclamations and liquefaction analyses are discussed including comparisons of the computed performance with the observations. Insights from the ongoing program of research on gravelly and hydraulically placed reclamations are also shared.

2 SITE DESCRIPTION

Wellington city was developed over the past 170 years after the European settlement in the 1850's. The original coastline from the 1850's is approximately 200 m to 500 m inland from the current revetment line delineating a belt of reclaimed land that increases in width towards the north along the waterfront and reaches its largest extent at CentrePort. The land between the original coastline and the current revetment line consists of reclaimed soils of varying age, construction methods, and soil thicknesses. The reclamations in the Wellington waterfront areas 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 rest of the reclaimed land by an old buried concrete seawall, which is depicted in Figure 1.

An aerial view of CentrePort is illustrated in Figure 1 highlighting details on key construction pe-riods, soils used for the reclamation, and some refer-ence buried structures.

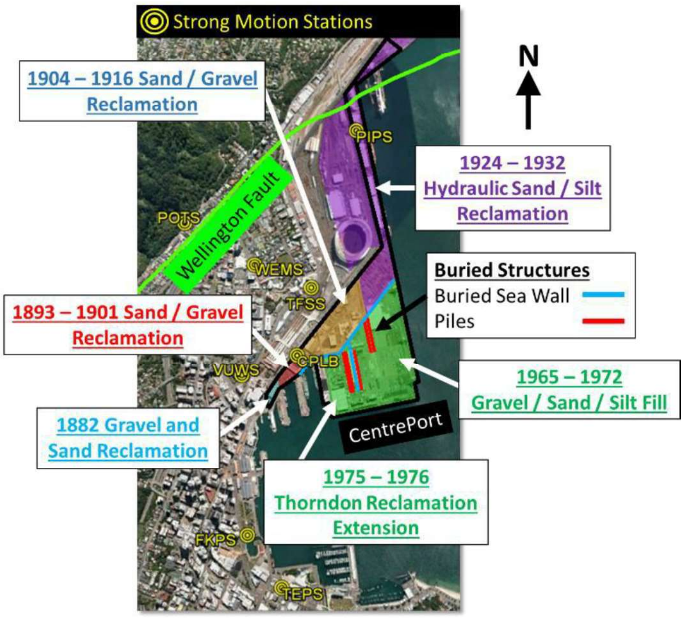

Figure 1. Aerial view of CentrePort showing the Wellington Fault, nearby strong motion stations, relevant buried structures, and reclamation regions indicating period of construction and soil materials used (base image from Google Earth^{TM}).

Two methods of construction were used for the CentrePort reclamations. The 1924-1932 reclama-tion consists of hydraulic fills that were constructed using dredged material (sandy and silty soils) from the original seabed in the vicinity of the reclamation works. The remaining, more recent and larger part of the reclamation were 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 coast-line. At CentrePort the gravelly reclamation has ap-proximately 10 m thickness immediately south of the buried seawall and increases to a maximum thickness of approximately 22 m along the southern edge of the Thorndon Extension. The top 3 m of the fill consist of densely compacted gravelly crust, be-low which are the relatively thick uncompacted fills. The fills sit atop a thin layer of marine sediments of interbedded sand, clay and silty clay, which is over-lying approximately 90-135 m thick Wellington Al-luvium composed of interbedded dense gravels and stiff silts.

3 EARTHQUAKE GROUND MOTION

On 14 November 2016, the M_w7.8 Kaikoura earth-quake occurred in the South Island of New Zealand. The complex rupture involving over 20 faults initiat-ed at the southern end of the source zone and pro-gressed northeast along the coastal area (Hamling et al. 2017). The approximate location of the earth-quake epicenter and the earthquake rupture sequence are indicated in Figure 2. The source-to-site distance (i.e. the closest distance from the causative faults to Wellington) was approximately 60 km (Cubrinovski et al. 2018).

Ground motions were recorded at several strong motion stations in the vicinity of the port (Figure 1) including records at a rock site (POTS), natural soil deposits (WEMS and TFSS), shallow reclaimed sites (VUWS), and deep reclaimed land sites (CPLB, PIPS, TEPS and FKPS). The 2016 Kaikoura earth-quake produced long duration of ground shaking with moderate amplitudes with horizontal peak ground accelerations of 0.25g (geomean of north-south and east-west components) at CentrePort. The ground motions reflect combined effects of site am-plification and basin geometry, which appear to be significant in Wellington (Bradley et al., 2018).

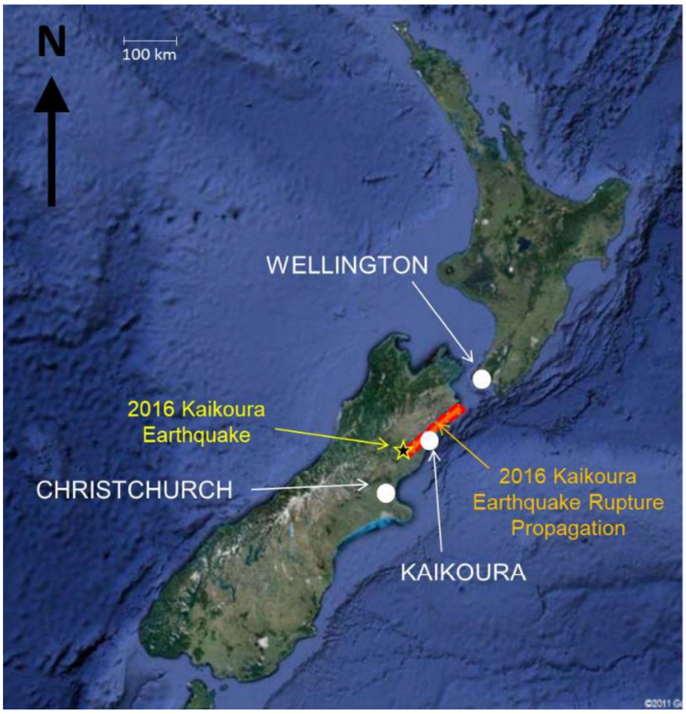

Figure 2. Approximate location of the 2016 Kaikōura Earth-quake epicenter and rupture sequence in relation to Wellington (base image from Google Earth^{TM}).

4 DETAILED SITE CHARACTERISATION

In the previous phase of this study, CentrePort rec-lamations were characterized using 47 CPTs, shear wave velocity measurements (Cubrinovski et al. 2018), and subsurface data from previous studies (Tonkin & Taylor Ltd. 2014). This study corrobo-rates previous findings with updated data from 55 additional CPTs successfully advanced in 2018.

A.P. van den Berg I-cones were used with a 218 Geomil Panther 100 rig with a push force of 106 kN for the 102 CPTs. Tests were performed with 10 cm^2 and 15 cm^2 cones with stainless steel and plastic fil-ters for the u_2 pore pressure transducers. Field opera-tions 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, the casing was extended beyond the depth of refusal, and then cone testing was continued. The locations of all 102 CPT sites are shown on Figure 3.

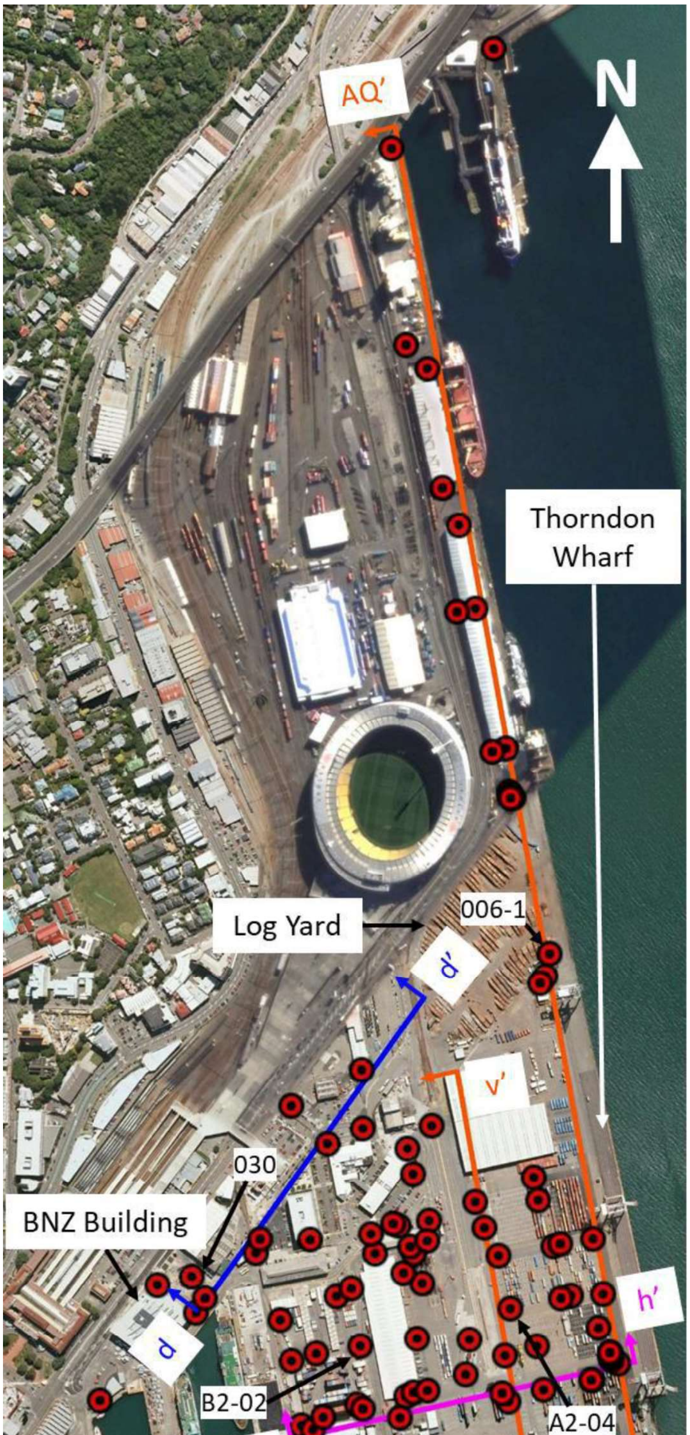

Figure 3. Overview of CentrePort showing 102 CPT locations and soil cross sections (base image from Google Earth™).

Figure 4 schematically illustrates characteristic soil profiles (updated from Cubrinovski et al. 2018) along four cross sections: v-v', AQ-AQ', h-h' and d-d' (locations are shown in Figure 3). These profiles summarize key features of reclamation soil units, the underlying marine sediments, and the Wellington Alluvium as characterized by the CPTs. Traces of cone tip resistance (q_c) for CPTs located along these cross sections are included. The q_c and soil behavior type index (I_c) based on Robertson (2016) values shown in the plots show characteristic ranges (25th and 75th percentiles) for typical soil units. The vertical scale of the cross sections is exaggerated to show details, which distorts the shape of the slopes and wharves. The slope geometry and bathymetry are also based on Tonkin & Taylor Ltd. (2014). The unit thicknesses between CPTs have been interpolated based on boreholes and observed trends.

The CPT data in the hydraulic fill (AQ-AQ') generally show low penetration resistances of silt-sand mixtures up to depths of 5 m to 10 m, overlying a 4 m thick clayey layer. From 12-20 m depth, sand and gravel alluvium layers with thickness of about 1.5 m are interbedded with thin silty and clayey soils. As illustrated in Figure 4, the old buried concrete seawall separates the region containing the older hydraulically dredged sandy/silty fill with the more recent end-dumped gravelly reclamation.

The gravelly fill (v-v' and h-h') is characterized by consistent traces of low tip resistance of q_c = 6.3-7.8 MPa and I_c values of 2.06–2.19. The relatively high values of I_c for gravelly soils imply that these gravel-sand-silt fills display soil behavior typical for fine-sand and coarse-silt mixtures. The CPT data confirm findings based on grain-size composition that finer fractions (sands and silts) dominate the matrix, and hence, governs the response characteristics of the gravelly fills rather than the gravel-size particles (Cubrinovski et al. 2017). The presence of loose-to-medium dense sand (i.e. q_c slightly above 10 MPa) from about 5 m to 12 m depth (i.e. below gravelly reclamation) was a characteristic feature of the CPTs in the Thorndon Reclamation where sandy ejecta was found on the ground surface following the 2016 Kaikoura earthquake.

The older 1904-1916 reclamations north of the buried sea wall (cross section d-d') show 2-5 m of gravel/sand/silt fill atop sandy soil. In this area, the thickness of the fill is largest near the BNZ building and decreases towards the log yard (Figure 3 depicts their locations). The CPTs provide consistent and detailed characterization of the fills including clear distinction between the gravel-sand-silt mixes and predominantly sandy fills, underlying marine sediment and Wellington Alluvium, and thickness of the stiff compacted fill crust.

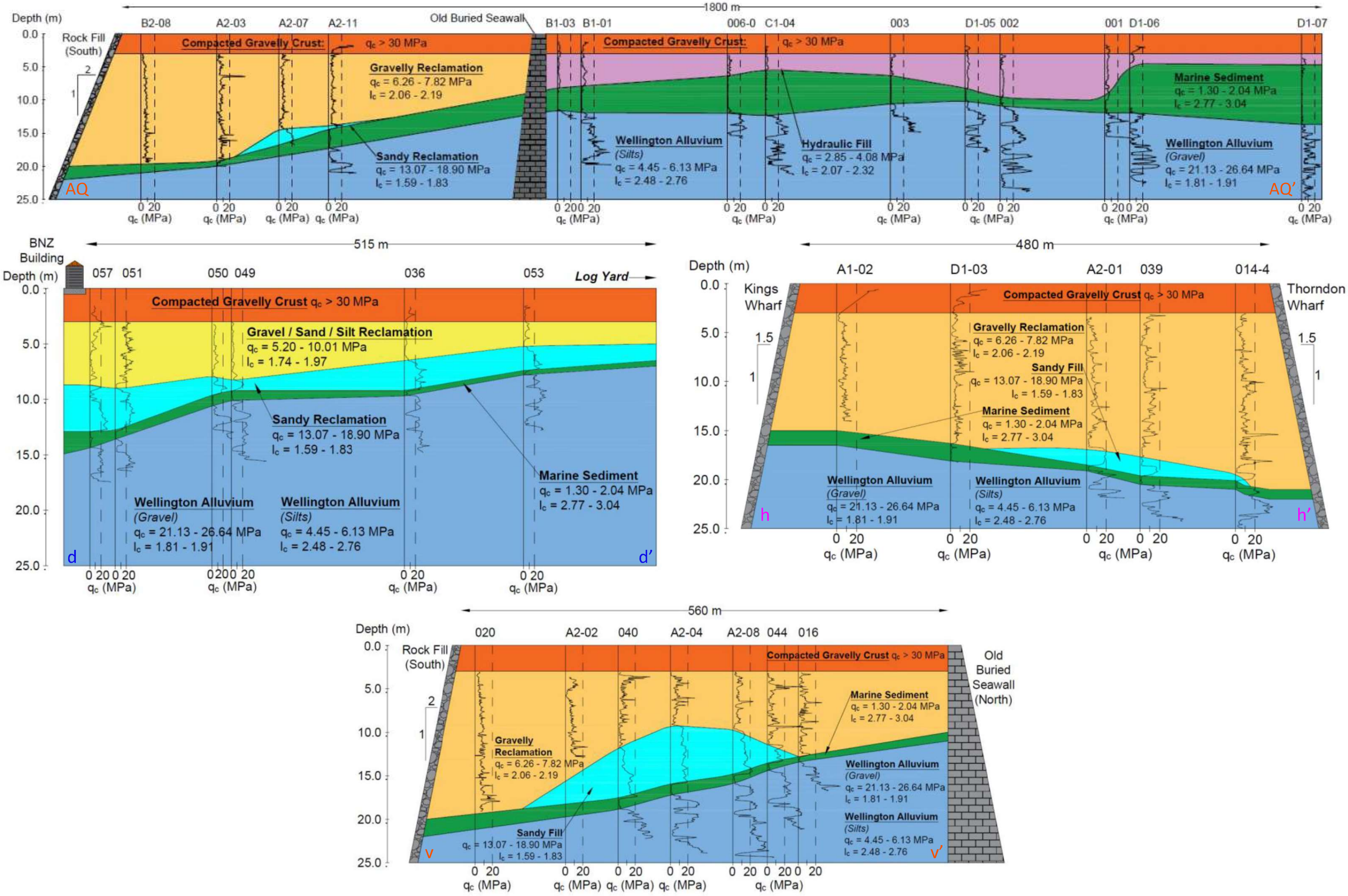

Figure 4. Cross sections depicting key soil units (vertical scale exaggeration 10 times). Top: AQ-AQ' (N-S); Left: d-d' (NE-SW); Right: h-h' (E-W); Bottom: v-v' (N-S). See Figure 3 for cross section and CPT locations. The q_c and I_c ranges are based on 25th to 75th percentile values for each soil unit across all representative CPTs.

5 OBSERVED LIQUEFACTION-INDUCED GROUND DEOFRMATIONS

The 2016 Kaikoura earthquake triggered widespread liquefaction and consequently severely damaged various buildings and wharves. Non-uniform and scattered liquefaction ejecta were observed on pavement surface of the port including traces of ejected silt and water to larger volumes of soil ejecta with thicknesses of up to 150-200 mm. Global deformation involved approximately 1 m of outward (seaward) movement of the reclamation slopes (edges) in unconfined directions, with characteristic liquefaction-induced lateral spread cracking and ground distress progressing in-land within the reclamation. Large vertical offsets on the order of hundreds of millimeters to above 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 can be found in Cubrinovski et al. (2017). Examples of the soil ejecta distribution and observed ground deformations for the Thorndon Container Wharf are depicted in Figure 5.

6 SIMPLIFIED LIQUEFACTION ASSESSMENT

The collected CPT data were used to evaluate liquefaction triggering and its consequences using state-of-the-practice simplified analysis procedures. In these analyses, the groundwater level estimates for in situ conditions are based on the measured pore water pressure (u_2) profiles from the CPT and pore water pressure dissipation tests performed at each of the CPTs. The total unit weight of the soil is assumed to be 19 kN/m^3 for the reclaimed fill. The fines content (*FC*) is estimated as 15% based on historical records and particle size distribution curves obtained from the ejecta samples (Cubrinovski et al. 2017). The soil behavior type index (I_c; Robertson 2016) criterion of $I_c < 2.6$ is used to identify soils susceptible to liquefaction. The simplified liquefaction evaluation procedure is conducted assuming a level ground condition for a M_w7.8 event with a PGA of 0.25g to represent the geomean of the shaking induced by the 2016 Kaikoura earthquake (Cubrinovski et al. 2018). Liquefaction triggering is evaluated using the Boulanger and Idriss (2014) CPT-based procedure, which compares the earthquake-induced cyclic stress ratio (*CSR*) to the cyclic resistance ratio (*CRR*) of the soil to estimate the factor of safety against liquefaction triggering. The probability of liquefaction triggering of *PL* = 50% is used for the back-analysis of this case history. The Zhang et al. (2002) procedure is used to estimate post-liquefaction reconsolidation settlement as an index of the effects of soil liquefaction.

This paper discusses the simplified liquefaction assessment of four representative CPT profiles for the 2016 Kaikoura earthquake. CPT B2-02 is a typical site in the Thorndon Extension Reclamation, which is the most recent reclamation of the port (i.e.

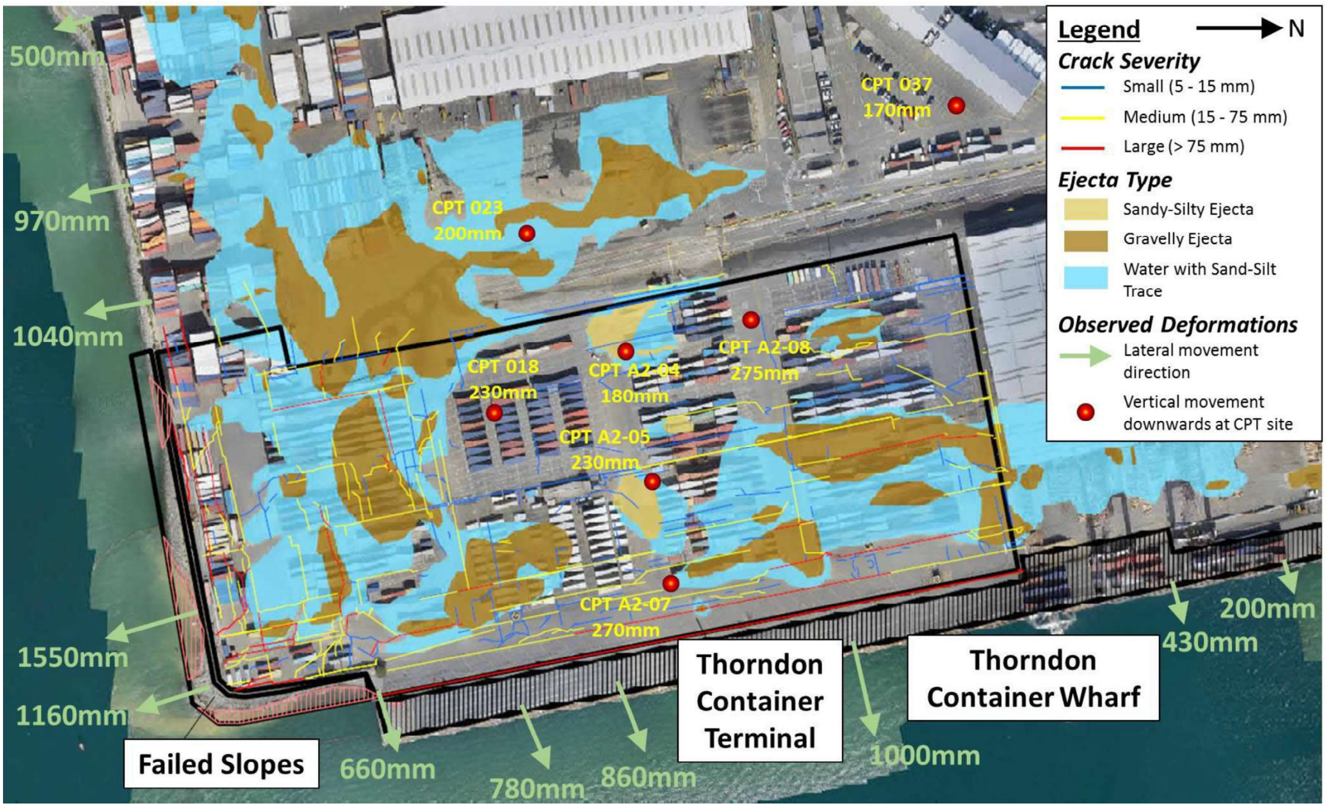

Figure 5. Location and magnitude of vertical and lateral displacements obtained during aerial UAS survey (from CARDNO; base image from Google Earth^{TM}). Severity of ground cracks and liquefaction ejecta map of the eastern part of CentrePort (Tonkin & Taylor 2014) are also shown. Measured vertical displacements from the UAS survey labelled on the map are < 5 m from the CPT site labelled. The predicted settlements from CPT-based simplified procedures for these labelled CPT sites are shown on Figure 7.

1975-1976), which contains end-dumped gravelly fill overlying marine sediments which sit atop Wellington alluvium. CPT A2-04 represents one of the few areas in the Thorndon Reclamation, which is a slightly older reclamation (i.e. 1969-1970), where silty/sandy gravel fills are atop sandy reclamation, below which is marine sediment and Wellington alluvium. CPT 006-1 represents a site with hydraulic fills, where up to 3 m of hydraulically-dredged sand slurries were deposited atop native marine sediment during the period of 1924 to 1932. CPT 030 is a typical site from the 1904-1916 reclamation north of the buried sea wall, which contains gravelly and sandy fill atop marine sediments at 12 m depth, below which lies the Wellington Alluvium at 13 m depth.

Figure 6 shows the CPT profiles of q_c and I_c, followed by the computed *CRR* and *CSR* profiles and post-liquefaction reconsolidation settlement profiles for the four CPTs discussed in this paper for the 2016 Kaikoura event. The results of the simplified liquefaction evaluation procedure indicate the *CRR* of the reclamation is well below the seismic demand of the 2016 Kaikoura earthquake (*CSR*). Hence, the Boulanger and Idriss (2014) CPT-based simplified procedure indicates that liquefaction should have been triggered at these sites and at most of the reclamation sites in CentrePort under the seismic demand of the Kaikoura earthquake. As discussed previously, widespread liquefaction effects (e.g. soil ejecta, and vertical and horizontal ground movements) were observed at the port after this event. Thus, the simplified CPT-based liquefaction triggering procedures provide generally consistent results with the field observations for these sites and this earthquake event, even for those sites containing a significant proportion of gravel-sized particles.

The Zhang et al. (2002) procedure estimates post-liquefaction reconsolidation vertical settlements on the order of 50 to 150 mm for these sites, which are, by and large, consistent with the observed settlements in these areas after the 2016 Kaikoura earthquake. Figure 7 compares the predicted liquefaction-induced vertical settlements to those observed for 12 sites where the CPT locations were within 5 m of measured vertical displacements by aerial surveys (some sites indicated in Figure 5). The estimated values of one-dimensional (1D) post-liquefaction volumetric-induced settlement are mostly lower than

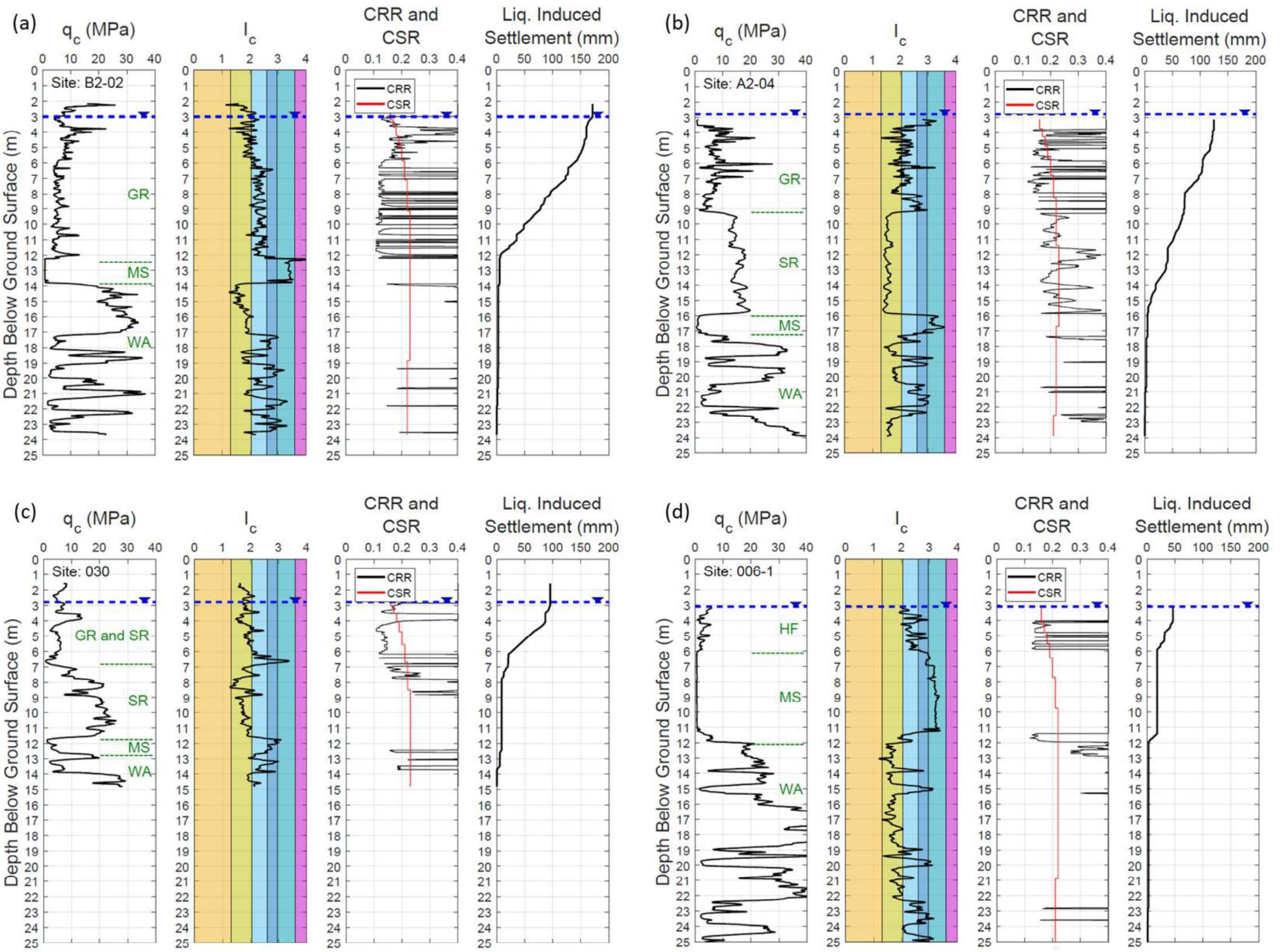

Figure 6. CPT tip resistance (q_c), soil behavior type index (I_c), cyclic resistance ratio (*CRR*), cyclic stress ratio (*CSR*), and post-liquefaction vertical settlement profiles calculated under the shaking demand of the 2016 Kaikoura event for four soil profiles: (a) CPT B2-02; (b) CPT A2-04; (c) CPT 030; and (d) CPT 006-1. See Figure 3 for CPT locations. GR denotes layers of gravelly reclamation, HF denotes hydraulic sandy fill, MS denotes marine sediments, SR denotes sandy reclamation, and WA denotes Wellington alluvium.

the vertical displacements measured at these locations. However, they are judged to be reasonable when considering that the measured vertical settlement at the port also includes the components of vertical movement due to loss of soil from ejecta and lateral spreading-induced horizontal ground movements near the reclamation edges (especially CPT sites 030 and 006-1 which are < 50 m from the reclamation edges). Additional work is warranted to scrutinize the results from the simplified procedures.

7 CONCLUSION

The 2016 M_w7.8 Kaikoura earthquake caused widespread liquefaction in the end-dumped gravelly fills and hydraulically-placed dredged sandy fills at CentrePort in Wellington, New Zealand. Significant volumes of soil ejecta and large permanent ground deformations of the fills were observed. Complex soil composition, fabric and structure of the reclamations posed challenges with regards to obtaining quality subsurface geotechnical data and assessing the liquefaction performance of the soils.

Robust CPT equipment and procedures were utilized to obtain high-quality subsurface data. The comprehensive investigations performed at the port provide detailed characterization of the fills including underlying marine sediments, Wellington Alluvium, and the thickness of the compacted fill crust at the ground surface. The soil behavior type index I_c values imply soil behavior typical for sand-silt mixtures, rather than gravel-size particles. This is in agreement with the measured low tip resistances and inferred dominant influence of the sand and silt fractions in the soil matrix of the fill based on the grain-size composition of the fill.

CPT-based liquefaction triggering and post-liquefaction reconsolidation settlement assessments identified loose zones of fill that likely produced the observed ejecta, vertical settlement, and lateral spread deformations at the port that resulted in severe damage. These simplified analyses predict liquefaction and are consistent with observations for the 2016 Kaikoura earthquake. Ongoing work will also examine the lateral movement at the port. Effective stress analyses will be performed to investigate their capability to capture the observed seismic performance of the facilities at the port.

REFERENCES

Boulanger, R.W. & Idriss, I.M. 2014. *CPT and SPT Based Liquefaction Triggering Procedures*. Report No. UCD/CGM-14/01, University of California, Davis.

Bradley, B.A., Wotherspoon, L.M., Kaiser, A.E., Cox, B.R. & Jeong, S. 2018. Influence of Site Effects on Observed Ground Motions in the Wellington Region from the Mw 7.8 Kaikoura, New Zealand Earthquake. *B. Seism. Soc. America*, **108**(3), doi.org/10.1785/0120170286.

Cubrinovski, M., Bray, J.D., de la Torre, C., Olsen, M., Bradley, B.A., Chiaro, G., Stocks, E. & Wotherspoon, L. 2017. Liquefaction Effects and Associated Damages Observed at the Wellington CentrePort from the 2016 Kaikoura Earthquake. *B. New Zealand Soc. EQ Eng.*, **50**(2): 152-173.

Cubrinovski, M., Bray, J.D., de la Torre, C., Olsen, M., Bradley, B.A., Chiaro, G., Stocks, E., Wotherspoon, L. & Krall, T. 2018. Liquefaction-Induced Damage and CPT Characterization of the Reclamation at CentrePort Wellington. *B. Seism. Soc. America*, **108**(3), doi.org/10.1785/0120170246.

Hamling, I.J., Hreinsdottir, S., Clark, K., Elliot, J., Liang, C., Fielding, E., Litchfield, N., Villamor, P., Wallace, L. & Wright, T.J. 2017. Complex multifault rupture during the 2016 MW 7.8 Kaikoura earthquake, New Zealand, *Science*, 2017, 356, 6334.

Robertson, P. 2016. Cone penetration test (CPT)-based soil behavior type SBT classification system – an update. *Canadian Geot. J.*, **53**(12), 1910-1927.

Tonkin & Taylor Ltd. 2014. *Thorndon Container Wharf Seismic Assessment Geotechnical Factual Report.* Prepared for CentrePort Limited. Ref No. 85369.001.

Zhang, G., Robertson, P.K., and Brachman, R.W.I. (2002) "Estimating liquefaction-induced ground settlements from CPT for level ground," *Can. Geotech. J.*, **39**, 1168-1180.

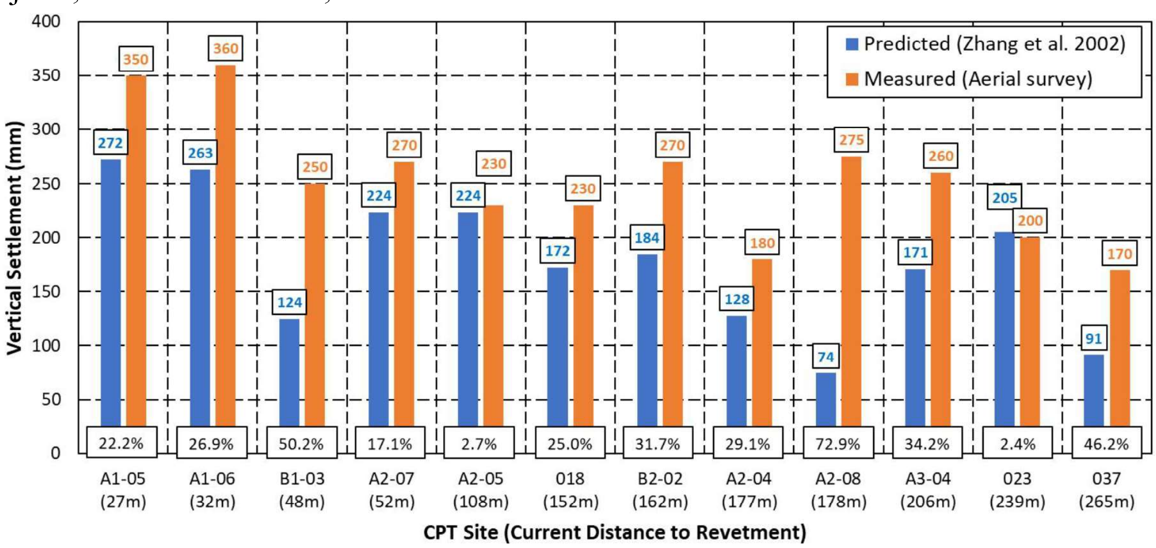

Figure 7. Settlements predicted using the Zhang et al. (2002) procedure compared to observed vertical displacements from UAS aerial survey at 12 CPT sites where observations were < 5 m from the CPT location. The sites are organized by distance to the current revetment. Percentage difference between the predicted and observed settlements (relative to observed) are also shown.