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Liquefaction assessment of reclaimed gravelly soils at CentrePort, Wellington

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ABSTRACT

Observations of liquefaction-induced damage at CentrePort, Wellington provide an opportunity to evaluate the applicability of state-of-the-art liquefaction evaluation methodologies on reclaimed soils. This study focuses on the application of simplified liquefaction assessment methods on the reclaimed gravelly soils at CentrePort for the 2013 Lake Grassmere, 2013 Seddon, and 2016 Kaikōura earthquakes. Liquefaction assessment of this reclamation poses several challenges due to its large percentage of gravel-sized particles making it difficult to obtain high-quality in situ data. Following the 2016 Kaikōura earthquake, three cycles of subsurface exploration were launched investigating the thick end-dumped gravelly fills and hydraulically-placed dredged-soil reclamations. This study utilizes the data from 121 Cone Penetration Tests (CPTs) to thoroughly characterise the reclaimed land in detail. Results of CPT-based liquefaction triggering and post-liquefaction reconsolidation settlement assessments using state-of-the-art procedures are discussed and compared with observed liquefaction manifestation and settlements. Recommendations are made on future work for this study.

1 INTRODUCTION

Many earthquakes in New Zealand's recent seismic history have resulted in major damage due to soil liquefaction, and there is a growing demand for reliable liquefaction assessment strategies. Investigation of liquefaction hazards of gravelly soils in particular, which are often found in port facilities, require additional attention. Currently, triggering and consequences of liquefaction are quantified using semi-empirical methods calibrated predominantly on sandy soil deposits, with few case histories involving reclaimed soils of various grain-size composition. Concerns are raised in whether current simplified procedures are applicable to non-standard soils such as the gravelly soils with sand and silt mixtures as found at CentrePort.

This paper presents and discusses results from 121 Cone Penetration Tests (CPTs) to characterise the reclamation and perform simplified liquefaction triggering analyses and estimate consequent settlements for three recent earthquake events. Key findings from the characterisation of the reclamations and liquefaction analyses are discussed including comparisons of the predicted settlements with the observed and measured settlements. Insights from the ongoing program of research 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 port of Wellington). The land between the original coastline and the current revetment line is reclamation of different age, method of construction, and thickness. The reclamations in the Wellington waterfront areas were constructed over three 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 1b. An aerial view of CentrePort is illustrated in Figure 1b highlighting details on key construction periods, soils used for the reclamation, and some reference old buried structures.

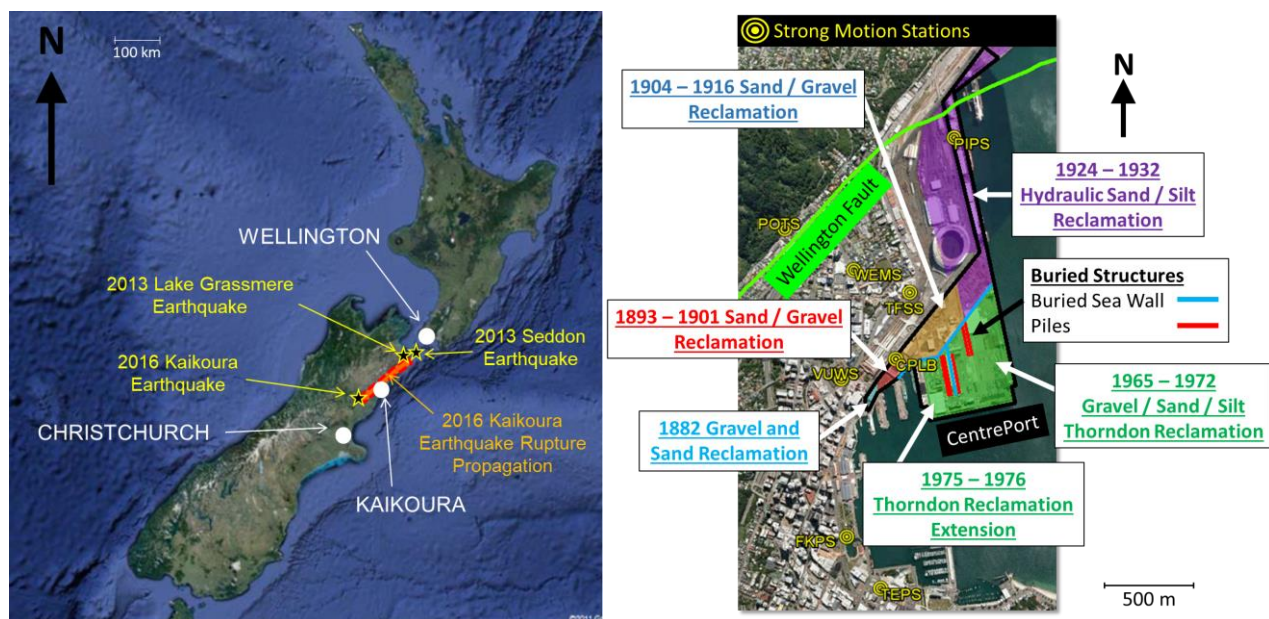


Figure 1: (a) Aerial view of the earthquake epicentre and rupture propagation for the 2016 Kaikōura earthquake, and epicentres for the 2013 Seddon and Lake Grassmere earthquakes; (b) Aerial view of CentrePort showing the Wellington Fault, nearby strong motion stations, old buried structures, and reclamations with different period of construction and soils used (base image from Google Earth™).

Two methods of construction were used for the CentrePort reclamations. The 1924-1932 reclamation 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 parts of the reclamation were constructed by end-tipping of gravelly soils from nearby quarries using truck and barge operations.

The top 3 m of the fill above the water table consist of a roller-compacted layer underlain by a relatively thick uncompacted fill. For the Thorndon Reclamation (green shading in Figure 1b), the thickness of the gravelly fill increases from about 10 m immediately south of the old buried seawall to approximately 22 m along the southern edge of the reclamation (Thorndon Extension). The fills sit atop a thin layer of Holocene beach material and marine sediments of 1-4 m thickness comprised of sands, clay, silty clay, and shell

fragments (Semmens 2010). These marine sediments overlies Pleistocene weathered sediments (Wellington alluvium), approximately 90 m to 135 m thick. The Wellington alluvium is composed of interbedded dense gravels and stiff silts. Greywacke bedrock underlies the Pleistocene sediments (Cubrinovski et al. 2018).

3 EARTHQUAKE GROUND MOTION

Three earthquake events with well-recorded ground motions were considered in this study for liquefaction assessment. These events are the M_w 6.5 Seddon earthquake (21 July 2013), M_w 6.6 Lake Grassmere earthquake (16 August 2013), and the M_w 7.8 Kaikōura earthquake (14 November 2016). Of these events, the Kaikōura earthquake caused the most extensive damage to CentrePort. This event was caused by a complex rupture involving over 20 faults, which initiated at the southern end of the source zone and progressed northeast (Hamling et al. 2017). The approximate locations of the earthquake sources and rupture propagation are indicated in Figure 1a. Due to the relatively small source zones for the scale of the figure, the source and rupture details of the two 2013 earthquake events are omitted. Source-to-site distances (R_{rup}) for the three events were 73 km for Lake Grassmere event (Tonkin & Taylor Ltd. 2014), 55 km for Seddon event (Tonkin & Taylor Ltd. 2014) and 60 km for the Kaikōura event (Cubrinovski et al. 2018).

Ground motions were recorded at several strong motion stations in the vicinity of the port (Figure 1b) including records at a rock site (POTS), natural soil deposits (WEMS and TFSS), reclaimed sites atop shallow native deposits (VUWS), and reclaimed sites atop deep natural deposits (CPLB, PIPS, TEPS and FKPS). The 2013 Seddon and Lake Grassmere earthquakes produced generally similar levels of ground motions in Wellington (Cubrinovski et al. 2018). The Seddon earthquake generated slightly higher Peak Ground Accelerations (PGA) of 0.22g geomean (16th to 84th percentile range: 0.21g-0.26g) at CentrePort (CPLB) than the Lake Grassmere earthquake with PGA = 0.15g geomean (16th to 84th percentile range: 0.13g-0.19g). The 2016 Kaikōura earthquake produced longer duration of ground shaking of moderate amplitudes with horizontal PGA of about 0.25g geomean (16th to 84th percentile range: 0.21g-0.30g) at CentrePort. The ground motions reflect complex effects of site amplification (local soil conditions) and basin geometry (basin-edge effects), which appear to be significant in Wellington (Bradley et al. 2018). All geomean PGA values presented in this paper are of north-south and east-west components of shaking.

4 DETAILED SITE CHARACTERISATION

In the first phase of this study, CentrePort reclamations were characterised using 47 CPTs, shear wave velocity measurements (Cubrinovski et al. 2018; Vantassel et al. 2018), and pre-earthquake subsurface data from Tonkin & Taylor Ltd. (2014). This study corroborates previous findings with updated data from 74 additional CPTs successfully advanced in 2018 over two additional cycles of subsurface testing. Tests were performed with 10 cm² and 15 cm² A.P. van den Berg I-cones. 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 with symbols in Figure 2.

Figure 3 schematically illustrates characteristic soil profiles (updated from Cubrinovski et al. 2018) along a cross section (transect shown in Figure 2). These profiles summarise key features of reclamation soil units, the underlying marine sediments, and the Wellington Alluvium, as characterised by the CPTs. Traces of cone tip resistance (q_c) for CPTs located along these cross sections are also included. The q_c and soil behaviour 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 geometry. The slope geometry and bathymetry are based on Tonkin & Taylor Ltd. (2014). The unit thicknesses between CPTs have been interpolated based on boreholes and observed trends.

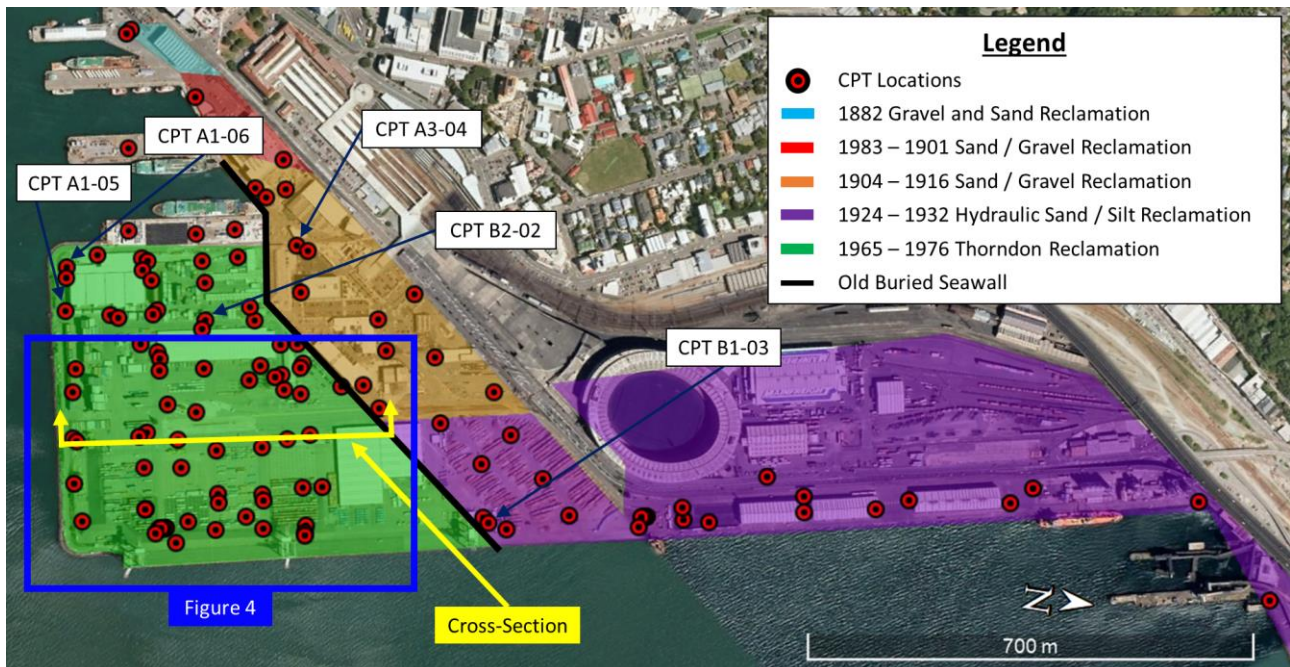


Figure 2: Aerial view of CentrePort showing reclamation zones, locations of the 121 CPTs, labels of some CPTs referred to in Figure 5, and a cross section transect for Figure 3 (base image from Google Earth™)

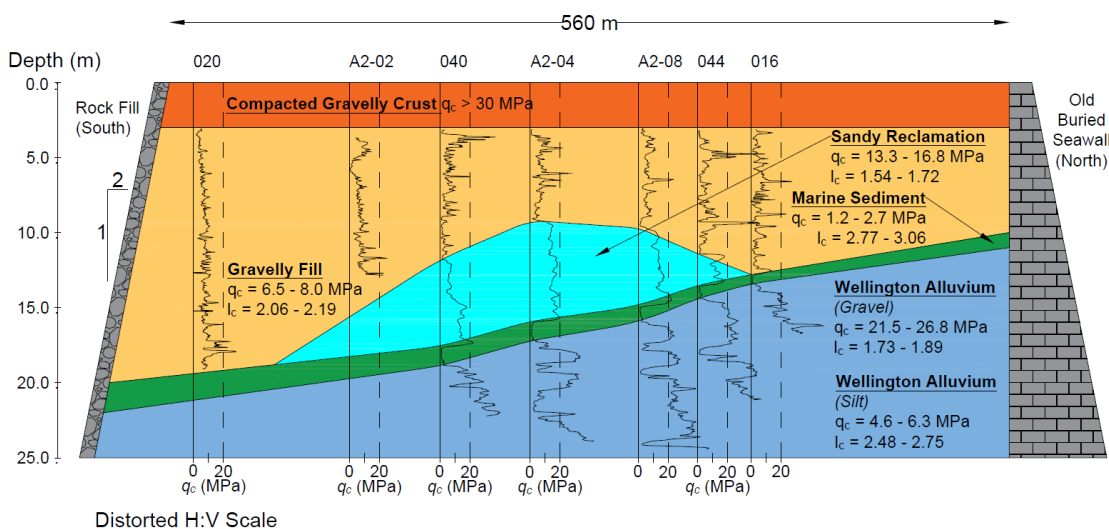


Figure 3: Cross section depicting key soil units at CentrePort as characterised by CPTs (vertical scale exaggeration 10 times). See Figure 2 for cross section location. The q_c and I_c ranges are based on 25th to 75th percentile values for each soil unit across all representative CPTs.

The gravelly fill is characterised by consistent traces of low tip resistance of $q_c = 6.5\text{--}8.0$ 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 behaviour typical for fine-sand and coarse-silt mixtures according to the Robertson (2016) characterisation scheme. 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 gravel-sand-silt mixture 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 for part of the CPTs in the Thorndon Reclamation where sandy ejecta was found on the ground surface following the 2016 Kaikōura earthquake. The underlying marine sediment is approximately 1.5 m thick.

5 OBSERVED LIQUEFACTION-INDUCED GROUND DEFORMATIONS

Damage inspections following the two 2013 earthquakes showed either no or negligible damage over most of the port area. All observed damage was reported to have most likely been a result of the Seddon earthquake, including lateral movement of approximately 250 mm at King's wharf (western end of Thorndon Reclamation) and over 100 mm along the south road. The Thorndon Extension slope suffered partial collapse in this event. Cracks were evident at the east and west edges of the reclamation adjoining King's Wharf and Thorndon Container Wharf. Vertical settlements around 50 mm (and as large as 90 mm) were observed after the Seddon earthquake, but little wharf damage and ground deformations were reported to have occurred due to the Lake Grassmere shaking (Tonkin & Taylor Ltd. 2014). The Seddon earthquake was reported to have caused some liquefaction-induced damage, while no damage was reported to have been associated with the Lake Grassmere earthquake (Tonkin & Taylor Ltd. 2014).

In contrast, the 2016 Kaikōura 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 of thicknesses 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 millimetres 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). Mapping of soil ejecta distribution and observed ground deformations for the Thorndon Container Wharf is shown in Figure 4 (adapted from Tonkin & Taylor Ltd. 2017).

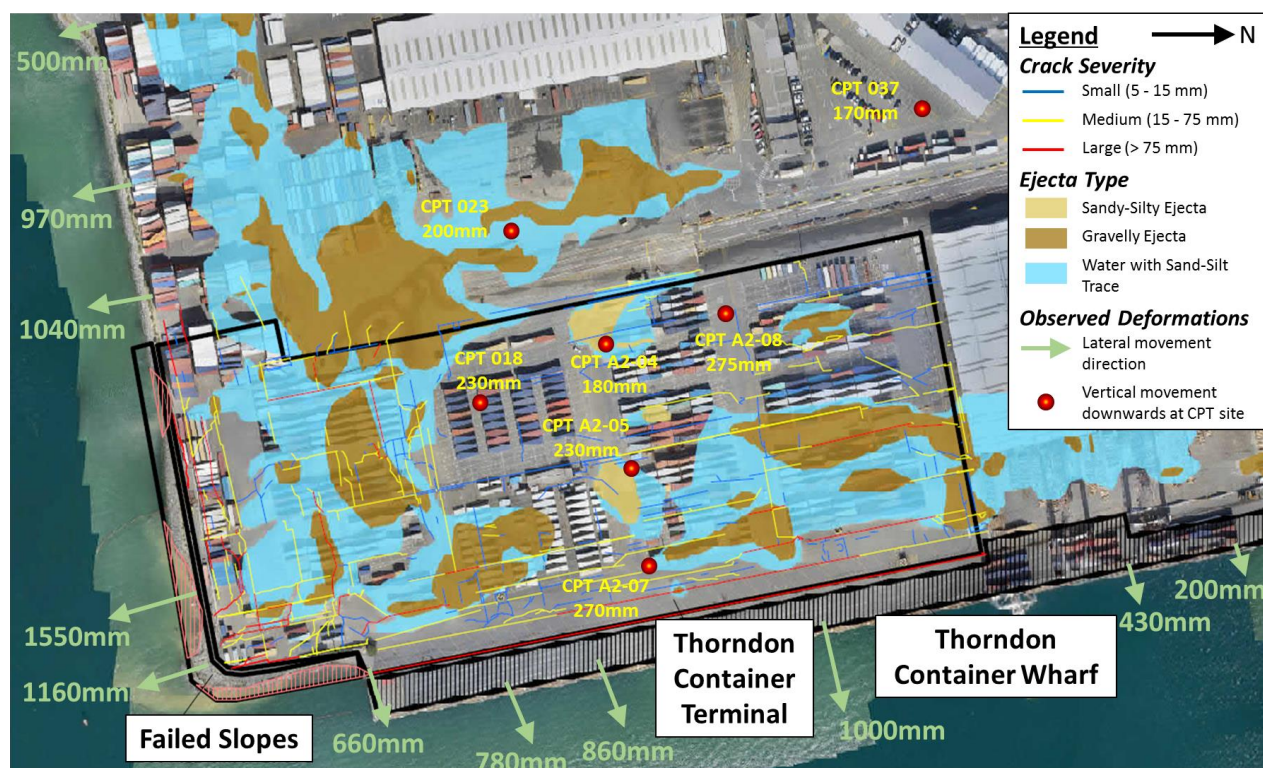


Figure 4: Map of Thorndon Reclamation highlighting lateral displacements, ground crack severity and liquefaction ejecta from aerial UAS survey (from CARDNO and drone video; Tonkin & Taylor Ltd. 2017). Also shown are locations of seven CPT sites and the associated measured vertical settlements after the 2016 Kaikōura earthquake measured using LIDAR surveys (referred to in Figure 5).

6 SIMPLIFIED LIQUEFACTION ASSESSMENT

The collected CPT data were used to evaluate liquefaction triggering and its consequences using simplified liquefaction assessment procedures for a free-field level ground condition. In these analyses, the groundwater level estimates were based on the measured pore water pressure (u_2) profiles from the CPT and pore water pressure dissipation tests performed. The fines content (FC) was approximated to 15% based on particle size distribution curves obtained from the ejecta and borehole samples (Cubrinovski et al. 2017). The soil behaviour type index (I_c ; Robertson 2016) criterion of $I_c < 2.6$ was used to identify soils susceptible to liquefaction. The magnitudes and PGA (geomean of shaking) for the 2013 and 2016 earthquakes summarised in Section 3 were used as input parameters. Liquefaction triggering was evaluated using the Boulanger and Idriss (2014) CPT-based procedure to estimate the factor of safety against liquefaction triggering. The probability of liquefaction triggering of $PL = 50\%$ was used for the back-analysis of this case history. The Zhang et al. (2002) procedure was then used to estimate post-liquefaction reconsolidation settlement.

Other publications within this study discussed results of simplified liquefaction assessment for representative CPT profiles from different reclamation zones for the 2016 Kaikōura earthquake (Bray et al. 2019, Dhakal et al. 2019). Details of the cyclic stresses and demands, along with estimated liquefaction-induced damage indices, for given CPTs are detailed in these publications. This paper focuses on comparing the settlement predicted by the Zhang et al. (2002) procedure, for each earthquake event. The observed/measured settlements are also presented to facilitate discussion on the performance of these simplified methods.

Figure 5 compares the predicted liquefaction-induced settlements to the settlement measurements from aerial LIDAR surveys for 12 CPTs for the 2016 Kaikōura earthquake (CPT locations are < 5 m from measured vertical displacements). A similar analysis could not be shown for the 2013 earthquakes as there was no aerial survey data with accurate settlement measurements collected following these earthquakes. The estimated values of one-dimensional post-liquefaction volumetric-induced settlement for the 2016 event are mostly lower than the vertical displacements measured at these locations. However, they appear 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 scrutinise the results from the simplified procedures.

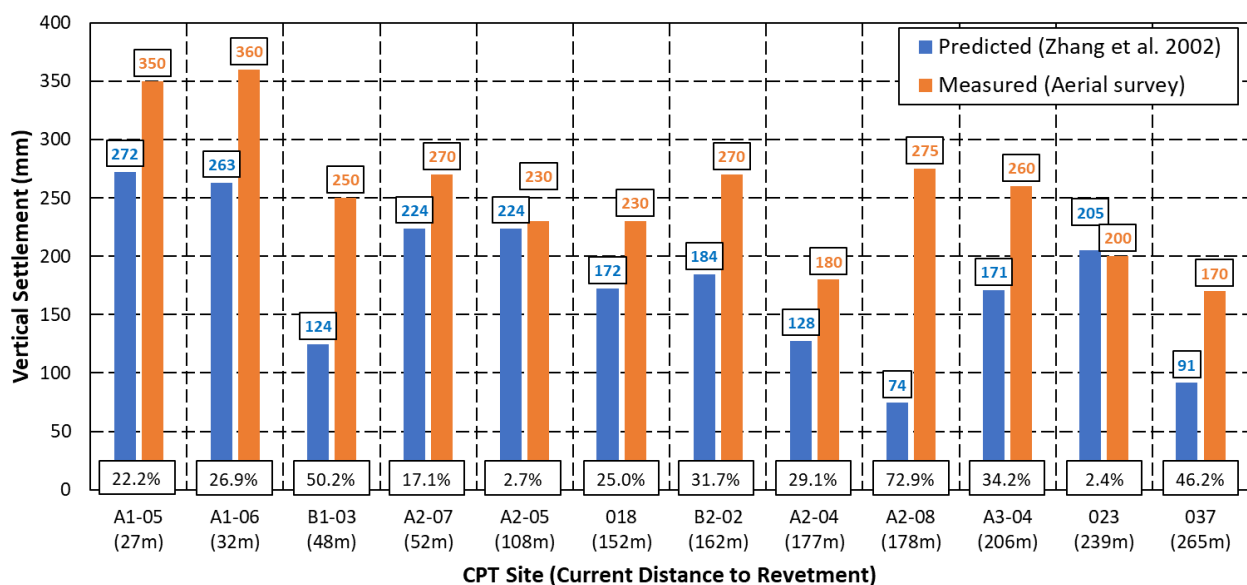


Figure 5: Settlements predicted using the Zhang et al. (2002) procedure compared to measured vertical displacements from UAS aerial survey at 12 CPT sites where observations were < 5 m from the CPT locations. Absolute percentage difference between the predicted and observed settlements are also shown.

Figure 6 shows the range of predicted settlements for the three earthquakes over a range of CPT sites using the Zhang et al. (2002) procedure. The range of observed/measured settlements are also included to facilitate comparisons. The range of predicted one-dimensional post-liquefaction volumetric-induced settlement from the Zhang et al. (2002) procedure for the 2013 Lake Grassmere and 2016 Kaikōura earthquakes are both lower than the range of observed/measured settlements at CentrePort. As stated before, this is reasonable if one considers that simplified methods do not account for additional vertical settlements due to loss of soil from ejecta and lateral spreading-induced deformation. The 2013 Lake Grassmere earthquake represents ground motions caused by a lower intensity of shaking, compared to the Kaikōura earthquake. In contrast, the settlements for the 2013 Seddon earthquake calculated using the Boulanger and Idriss (2014) followed by the Zhang et al. (2002) simplified procedures appears to slightly overpredict the observed settlements.

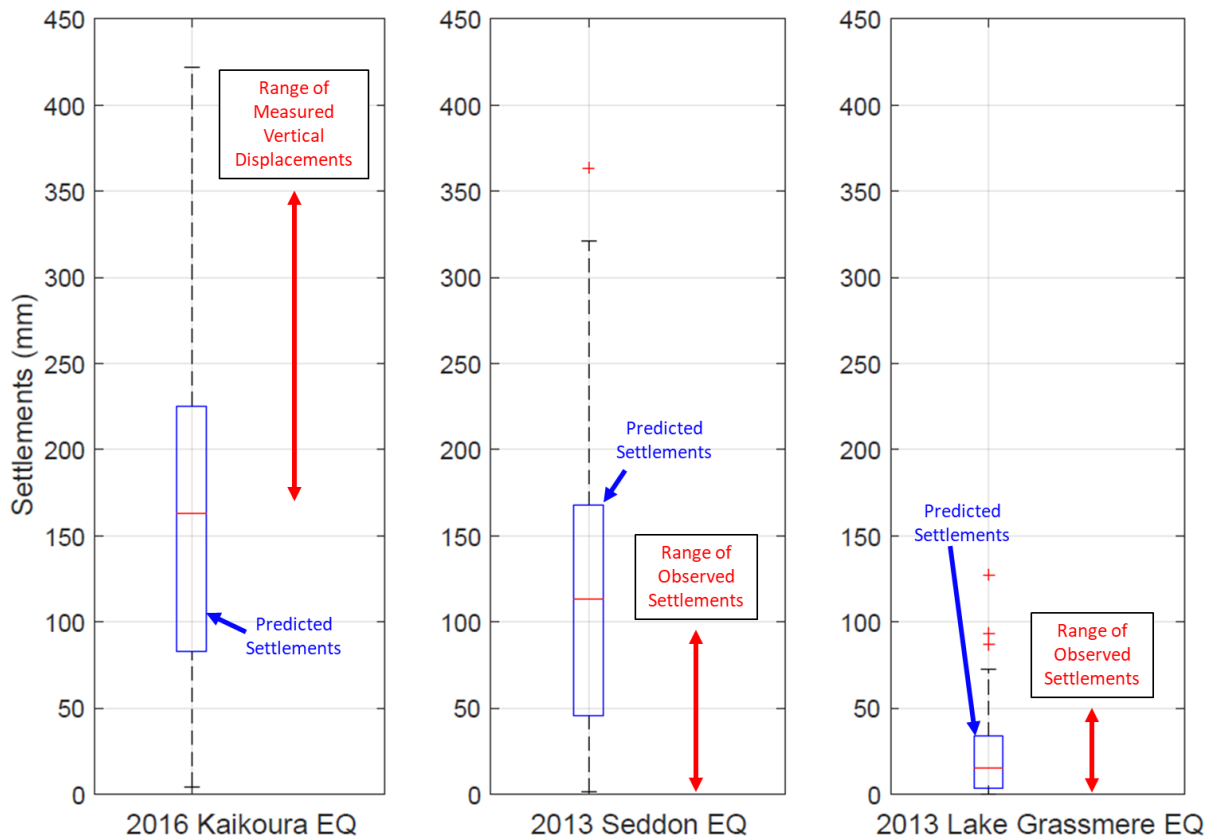


Figure 6: Box and whisker plot showing the range of predicted settlements across all 121 CPTs in the Thorndon Reclamation zone for the 2016 Kaikōura, 2013 Seddon, and 2013 Lake Grassmere earthquakes. Also shown are the associated range of measured settlements for the 2016 Kaikōura earthquake based on LIDAR surveys (Cubrinovski et al. 2018), and the associated range of estimated settlements for the 2013 earthquake events based on hand measurements during post-earthquake damage assessment of CentrePort (Tonkin & Taylor Ltd. 2014).

These simplified liquefaction procedures capture reasonably well the liquefaction triggering characteristics and approximate range of settlements for the high-level and low-level shaking intensities. Figure 6 illustrates the range of observed settlements (from Tonkin & Taylor Ltd. 2014) was below predicted values for two such representative events. In contrast, simplified methods appear to be slightly overpredicting liquefaction-induced damage for moderate-level shaking events such as the 2013 Seddon earthquake.

Additional work is warranted to scrutinise these simplified procedures and the applicability of its various components, and to analyse the lateral spreading hazard at the port. Interaction and influence with earth retention systems and wharf structures are also to be examined. Ongoing work involves further examining these issues through nonlinear effective stress analyses of representative soil profiles and cross sections.

7 CONCLUSION

Recent seismic activity has caused different levels of liquefaction-induced damage in end-dumped gravelly fills and hydraulically-placed dredged sandy fills at CentrePort in Wellington, New Zealand. The complex soil composition, fabric and structure of the reclamations pose challenges with regard to obtaining quality subsurface geotechnical data and assessing the liquefaction performance of the soils using state-of-the-art simplified methods. Scrutiny in the performance of these methods is necessary. Robust CPT equipment and procedures were utilised to obtain high-quality subsurface data and conduct liquefaction triggering and post-liquefaction reconsolidation settlement assessments. A key fill characteristic allowing for a successful use of CPT investigations was that silt and sand fractions of the fill control the soil matrix of the gravel-sand-silt mixture. Predicted vertical settlements were consistent with observations for the 2016 Kaikōura earthquake. The simplified procedures predict some triggering of liquefaction for the 2013 Lake Grassmere earthquake, largely matching observations. However, these methods slightly overpredicted the extent of liquefaction triggering and damage expected for the moderate-level shaking induced by the 2013 Seddon earthquake. Ongoing work will also examine the lateral movement characteristics at the port. Effective stress analyses will be performed to gain additional insights in the performance of reclamations and structures at the port.

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