Comparative Liquefaction Triggering Assessment of Gravelly Reclamations Using the CPT, DPT, and Shear-Wave Velocity

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ABSTRACT

Major challenges are encountered in characterizing and performing liquefaction assessment of gravelly soils since performing traditional in-situ tests, such as the Cone Penetration Test (CPT), in gravelly soils can be challenging, and since gravelly soils are not well-represented in existing case history databases used to develop semi-empirical methods for liquefaction assessment. This has been the primary reason for the ongoing efforts to develop methods based on other invasive tests, such as shear-wave velocity (V_s), and penetration tests with larger probes and greater energy delivered to the rod, such as the Dynamic Cone Penetration Test (DPT). While CPT-based liquefaction analyses have been comprehensively studied, limited research has been conducted comparatively evaluating the performance of the other two methods. This paper performs liquefaction triggering assessment of gravelly reclamations using data from the well-documented case history of the port of Wellington (New Zealand) using CPT, DPT, and V_s measurements. Results show that while the V_s measurements overestimate liquefaction resistance, the DPT and CPT agreed relatively well with observations from past earthquakes due to the greater sensitivity of these test methods to soil density and stratigraphy.

Keywords: Liquefaction, Gravelly soil, Cone Penetration Test, Dynamic Cone Penetration Test, Shear-wave velocity

1. Introduction

Semi-empirical methods for liquefaction triggering assessment were developed primarily using liquefaction case histories of sandy soils, and gravelly soils are currently not well-represented in liquefaction databases. The presence of coarse gravels in liquefiable soils has been shown to significantly affect the liquefaction and penetration resistances through the effects of particle size and packing of the soil (Tokimatsu 1988), while well-graded gravelly mixtures may show varying types of behavior ranging from that of silty sand to that of clean gravel depending on the proportion and role of different fractions in the soil mixture (Kokusho and Tanaka 1994; Cubrinovski et al. 2019). Therefore, the applicability of traditional sand-based liquefaction methods, such as ones based on the Cone Penetration Test (CPT), to gravelly soils has been shown to be dependent on the proportion and role of the different fractions in the mixtures (Dhakal et al. 2022).

On the other hand, there have been ongoing efforts to develop methods based on other invasive tests, such as shear-wave velocity (V_s), and penetration tests with larger probes and greater energy delivered to the probe, such as the Dynamic Cone Penetration Test (DPT), which can more easily be performed in gravelly soils. However, these methods are results of relatively more recent development and standardization, and their performance compared to traditional CPT-based methods is still unclear.

In this paper, CPT profiles from a well-documented case study in CentrePort, Wellington (New Zealand) are used to compare semi-empirical liquefaction triggering results of well-graded gravelly reclamations. Liquefaction case histories of gravelly soils are first examined to identify common characteristics. On this basis, CentrePort, which is shown to have common features with other case histories of liquefied gravelly soil, is used as a case study for comparison between the CPT-based, V_s-based, and DPT-based liquefaction triggering assessment.

2. Liquefaction of Gravelly Soils

2.1. Liquefaction Case Histories

While gravel was historically considered to be less susceptible to liquefaction than sand, several case histories of liquefaction in gravelly soils have been reported. Figure 1 summarizes the grain-size distribution curves of liquefied gravelly soils from case histories over nine separate earthquakes (refer to Dhakal et al. 2022 for further discussion of the case histories). The figure illustrates a very common feature in that the gravel content (*GC*; percentage of soil particles, by mass, with an equivalent diameter larger than 2 mm) is typically between 30% and 80%, with a fines content (*FC*; percentage of soil particles, by mass, with an equivalent diameter smaller than 0.075 mm) typically in the range between 5% and 15%. Thus, case histories of liquefied gravelly soils generally contain 50–70% mostly fine-to-medium sized gravels and 30% or more sand and silt.

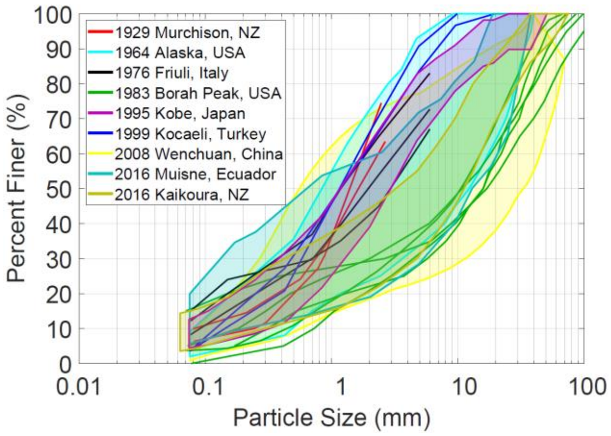

Figure 1. Grain-size distribution curves of liquefied gravelly soils (from Dhakal et al. 2022).

The presence of 20-30% or more finer sand- and silt-sized particles is an important compositional characteristic that is common for the case histories that exhibited a high liquefaction potential of gravelly soils. This fill composition is distinctly different from clean gravel deposits and are therefore herein referred to as well-graded gravel-sand-silt (G-S-S) mixtures.

2.2. In-Situ Testing for Liquefaction Assessment

Despite its advantages, performing a CPT in gravelly soil is inherently difficult because of interaction of the cone with gravel-sized particles that are large relative to the probe-size (Tokimatsu 1988). This has been the primary reason for the use of V_s in the liquefaction assessment of gravels (Kayen et al. 2013), and for the ongoing efforts to develop penetration tests with larger probes and greater energy delivered to the probe, such as the DPT (Cao et al. 2013). Existing CPT-based liquefaction assessment methods still include in-situ testing in gravelly soils, though the number of case histories involving gravels is quite limited. For example, only 4% of the Boulanger and Idriss (2014) CPT-based liquefaction database involves confirmed gravelly sites. The liquefaction triggering database is therefore dominated by case histories on sandy soils, and empirical field-based test methods evidently lack a robust database for liquefaction assessment of gravelly soils.

While the above challenges are prevalent for clean gravels with high *GC* in the range of 50–100%, the behaviour of G-S-S mixtures is affected by both the proportion and role of different soil fractions in the soil matrix. Hence, even though some fills can be classified as gravelly by grain-size composition, as they contain at least 50% gravel-sized particles by mass, the presence of at least 20-30% sand and silt may be sufficiently large for the finer silty sand fraction to govern the deformational behaviour of the soil mixture and hence control the response during earthquake shaking and penetration testing (Kokusho and Tanaka 1994; Cubrinovski et al. 2019). This implies that in-situ test methods such as the CPT, and associated liquefaction assessment procedures developed for sands, may be applicable to such G-S-S mixtures, at least for some cases or under certain conditions (Flora et al. 2012, Cubrinovski 2019; Dhakal et al. 2022).

3. CentrePort Case Study

3.1. Background

This paper focuses on the case study of CentrePort, which occupies approximately 0.5 km^2 of land within the Wellington city waterfront in New Zealand. Majority of the land was constructed through a water sedimentation process by end-tipping gravelly soils, sourced from nearby quarries, into the sea. The largest portion of CentrePort (i.e., Thorndon reclamation) has 7–22 m thick G-S-S fill, constructed between 1965 and 1976. The Thorndon reclamation is generally uniform, though it includes an isolated region where sandy fill with variable thickness (up to 10 m thick) sits beneath the G-S-S fill. The Thorndon fill (G-S-S and sand) was constructed with no compaction effort below approximately 3 m depth (coinciding with the approximate depth to water table) and is therefore in a loose state. Details of a comprehensive site characterization of CentrePort reclamations based on over 100 CPTs can be found in Dhakal et al. (2020a; 2020b).

3.2. Observed Liquefaction-Induced Damage

Three significant earthquakes with different intensities of ground motions affected CentrePort in 2013 and 2016. Ground motions were recorded at several strong motion stations within and in the immediate vicinity of the port during the 21 July 2013 moment magnitude M_w6.6 Cook Strait earthquake, the 16 August 2013 M_w6.6 Lake Grassmere earthquake, and the 14 November 2016 M_w7.8 Kaikōura earthquake. CentrePort experienced minor-to-moderate levels of shaking in these events with recorded horizontal surface peak ground acceleration (*PGA*) ranges (±1 standard deviation) of 0.20–0.31g, 0.18–0.27g, and 0.12–0.19g for the Kaikōura, Cook Strait, and Lake Grassmere earthquakes, respectively.

The Kaikōura earthquake triggered widespread liquefaction in the G-S-S reclamations causing over 1 m of lateral displacements due to spreading, over half a meter of settlement of the fill, and large areas covered with thick gravelly ejecta. Two wharves along the perimeter of the reclamation were damaged beyond repair, and several buildings on shallow and deep foundations suffered substantial damage including severe spreading-induced damage to a building on shallow foundations. The liquefaction-induced land damage was documented with ejecta and settlement patterns carefully analyzed to develop liquefaction damage maps throughout the port (Cubrinovski et al. 2017; Dhakal et al. 2020a; 2020b). While severe liquefaction-induced damage was observed over most of the Thorndon gravelly reclamation for the 2016 Kaikōura earthquake, the two earthquakes in 2013 largely caused none-to-minor levels of damage throughout the port, with the exception of localized severe damage along the unconfined southern edge of the port.

3.3. Site Investigation

After the Kaikōura earthquake, a comprehensive site exploration program was performed in multiple stages to characterize the subsurface conditions at CentrePort including 75 CPTs advanced in the Thorndon reclamation (Dhakal et al. 2020a; 2020b). The results from these CPTs are summarized with the shaded profiles in Figure 2 indicating the 25th and 75th percentile values of the measured cone tip resistance (q_c), soil behavior type index (I_c), and q_c corrected for overburden pressure (q_{c1N}) across all 75 CPTs in the Thorndon G-S-S fill. Superimposed in the figure with a solid line is one typical CPT trace (CPTC2-02).

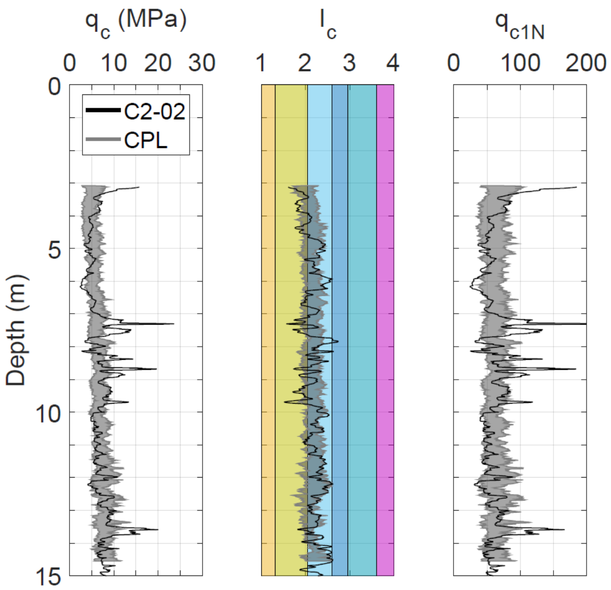

Figure 2. Measured cone tip resistance (q_c), soil behavior type index (I_c), and q_c corrected for overburden pressure (q_{c1N}) of G-S-S fills from one representative profile at CentrePort (denoted C2-02). The shaded region indicates 25–75% values for G-S-S fills at all 75 CPTs performed in CentrePort Thorndon G-S-S fill (denoted CPL).

The G-S-S fill consistently shows characteristic values of q_c = 4–10 MPa, I_c = 1.8–2.3, and q_{c1N} = 50–80 throughout its thickness. There are several spikes in the q_c and q_{c1N} trace of the selected CPT that are associated with lower I_c values. These spikes or instances of a sharp increase in the penetration resistance are reflective of the cone interaction with larger gravel particles. Importantly, however, the majority of the profile consistently shows I_c and q_{c1N} values typical for silty sand. Hence the CPT data indicate dominant effects of the finer sand and silt fractions in the G-S-S mixture, while coarser gravel particles have only a minor influence, as manifested by the occasional spikes. These CPT characteristics further support the premise for the applicability of sand-based liquefaction methods to CentrePort G-S-S fills due to the governing influence of the silty sand fraction in the soil matrix.

DPTs were performed in 2019 and reported in Roy et al. (2023) at six locations in the Thorndon reclamation. The tests employed a penetrometer consisting of a 74 mm diameter cone tip driven by a 63.5 kg hammer with a free fall height of 0.76 m using a 60 mm drill rod. The DPT provides a nearly continuous record of the blow count, N, which represents the number of hammer blows to drive the penetrometer through a 30 cm interval. To provide increased resolution, raw blow counts are typically reported at every 10 cm and multiplied by three to get the equivalent N for 30 cm of penetration. Since the test regime at CentrePort produced less energy than that supplied by the standard DPT (typically with a larger 120 kg hammer and a free fall height of 1 m), the blow counts are corrected using a hammer energy ratio, thus correcting N to N_{120}. The blow count over 30 cm of penetration is then corrected for overburden stress and reported as N'_{120}.

V_s has also been measured in 2019 in two locations within the Thorndon gravelly reclamation using the direct-push cross-hole (DPCH). The V_s data were measured at 0.5–1 m depth interval between borehole pairs approximately 3 m apart.

Overall, CentrePort provides an extremely well-documented case history including recorded ground motions for several earthquakes within the port, detailed liquefaction observations, and comprehensive high-quality subsurface investigations, which makes it appropriate for scrutiny and comparison of liquefaction assessment methods based on different in-situ test methods, which is the focus for the rest of the paper.

4. Comparative Triggering Assessment

4.1. Analysis Methodology

The CPT-based analyses are the primary efforts of this study and have been rigorously considered in previous literature (Dhakal et al. 2020a; 2020b; 2022). Therefore, results of triggering analyses based on the DPT and V_s data are presented for a representative profile in the Thorndon G-S-S reclamation under the seismic demand of all three earthquakes with the objective to compare with the results of the CPT-based analyses and gain insights on the reasons for any discrepancies. Note that the DPT-based analysis has been performed for several more CentrePort profiles and scrutinized to much greater detail by Roy et al. (2023).

For both sets of analyses, results are shown as profiles of the measured data corrected for overburden stress (i.e., N'_{120} or V_{s1}), cyclic resistance (CRR), and seismic demand (CSR). Results from a CPT located within a few meters of the location of the DPT or V_s profile are also shown as q_c, I_c, CRR, and CSR profiles. To facilitate fair comparisons with the CPT-based triggering results, the same input unit weight (19 kN/m^3), groundwater table (~3 m depth), and FC estimates as the CPT-based analyses are adopted in the DPT- and V_s- based analyses. Additionally, to show results of all three earthquakes together, all CRR values are correlated to penetration resistance for a reference M_w and overburden stress of 7.5 and 100 kPa (i.e., denoted CRR_B), and CSR is corrected to the same reference values via the correction factors MSF and K_σ (i.e., denoted CSR_B), respectively, in the CPT, DPT, and V_s analyses. The P_L = 50% triggering curves used for the CPT (Boulanger and Idriss 2014), DPT (Rollins et al. 2021), and V_s (Kayen et al. 2013) analyses are shown in Figure 3.

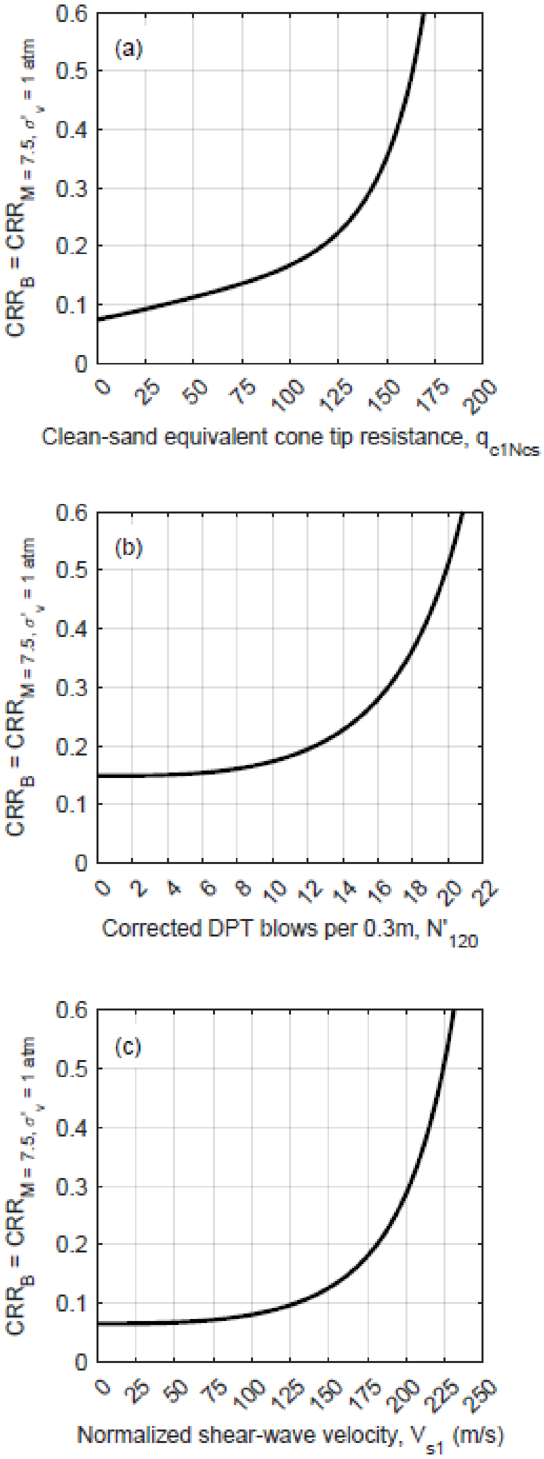

Figure 3. Liquefaction triggering curves with P_L = 50% for the (a) CPT-based (Boulanger and Idriss 2014), (b) DPT-based (Rollins et al. 2021) and (c) V_s-based (Kayen et al. 2013) methods, for M_w7.5 and σ'_{vo} = 1 atm.

4.2. DPT-Based Triggering Analysis

Results of the DPT- and CPT- based triggering analyses are shown in Figure 4 for tests performed next to one another. The G-S-S fill from 3 m to 12.5 m depth shows characteristic values of N'_{120} in the range of 4 to 7, and consistently below 10 throughout depth. This is in agreement with the range of q_c (6.5–8 MPa), I_c (1.9–2.3), and q_{c1N} (50–80) values from the CPT, whereby both the DPT and CPT result in penetration resistances typical of sands and silts. Like the CPT, the DPT exhibits low penetration resistances in the G-S-S mixture, typical of sands and silts, which are much lower than those typical for coarser and rounder alluvial gravelly fill. Figure 4 also illustrates the key advantage of the DPT, compared to the CPT, in that the DPT is less affected by the presence of larger gravel particles in the Thorndon fills. This manifests in two ways.

Firstly, while all DPTs were successfully performed in the first attempt, the CPTs occasionally hit refusal, which required further drilling through impenetrable strata before testing continued and can result in small layers of missing CPT data.

Secondly, as compared to the CPT profiles that exhibits occasional spikes in penetration resistance, the DPT yields relatively smooth profiles of N'_{120}. The larger diameter of the DPT cone along with the greater energy delivered to the rod means the penetration resistance reflects the average stress over a larger zone of influence of soil ahead of the probe and is less influenced by small changes in the particle sizes. The DPT delivers substantial excessive energy above the minimum force required to penetrate the soil, resulting in the test being less influenced by gravel-sized particles and exhibiting more stable resistances relative to the CPT. It is important to note that since the CentrePort G-S-S reclamations contain significant portions (> 30%) of sand and silt content, with most of the gravel particles being fine-to-medium (< 19 mm) sized, and CPTs in these fills being performed using larger 15 cm^2 cones, only isolated spikes (of secondary importance) are observed in the CPT.

Results of the triggering analyses (Figure 4d) indicate the seismic demand (i.e., CSR_B) for the Kaikōura event is considerably higher than CRR_B throughout the depth of the G-S-S deposit, therefore estimating a factor of safety for liquefaction triggering below one. The seismic demand for the Lake Grassmere event is considerably lower than CRR_B, hence estimating a factor of safety for liquefaction triggering above one. These results are consistent with the CPT-based results (Figure 4e) and observations. On the other hand, the seismic demand of the Cook Strait earthquake is very close to the CRR_B values. Like the CPT, the DPT-based assessment results suggest the seismic demand induced by the Cook Strait earthquake is relatively close to the liquefaction triggering threshold for the G-S-S fills. Overall, similar liquefaction triggering analysis outcomes are obtained for the DPT- and CPT- based assessments.

It is important to also recognize that the results highlight a key advantage in the CPT-based assessment compared to the DPT in that the CPT provides a description of the soil behaviour type using I_c, which makes it possible to identify non-liquefiable soil layers within the profile. For example, the CPT indicates non-liquefiable soft soil in Figure 4 from 13.5 m to 14.5 m depth where $I_c \approx 3.1$ (i.e., the native marine sediments sitting below the reclamation fill). The DPT alone cannot identify such non-liquefiable layers without referring to borelog descriptions, performing further index testing of the soil layer, or referring to the nearby CPT profile. Without such information, one may estimate this layer as liquefiable in the DPT-based analysis and hence estimate triggering, as shown in Figure 4d where a low CRR_B is calculated in the DPT-based assessment.

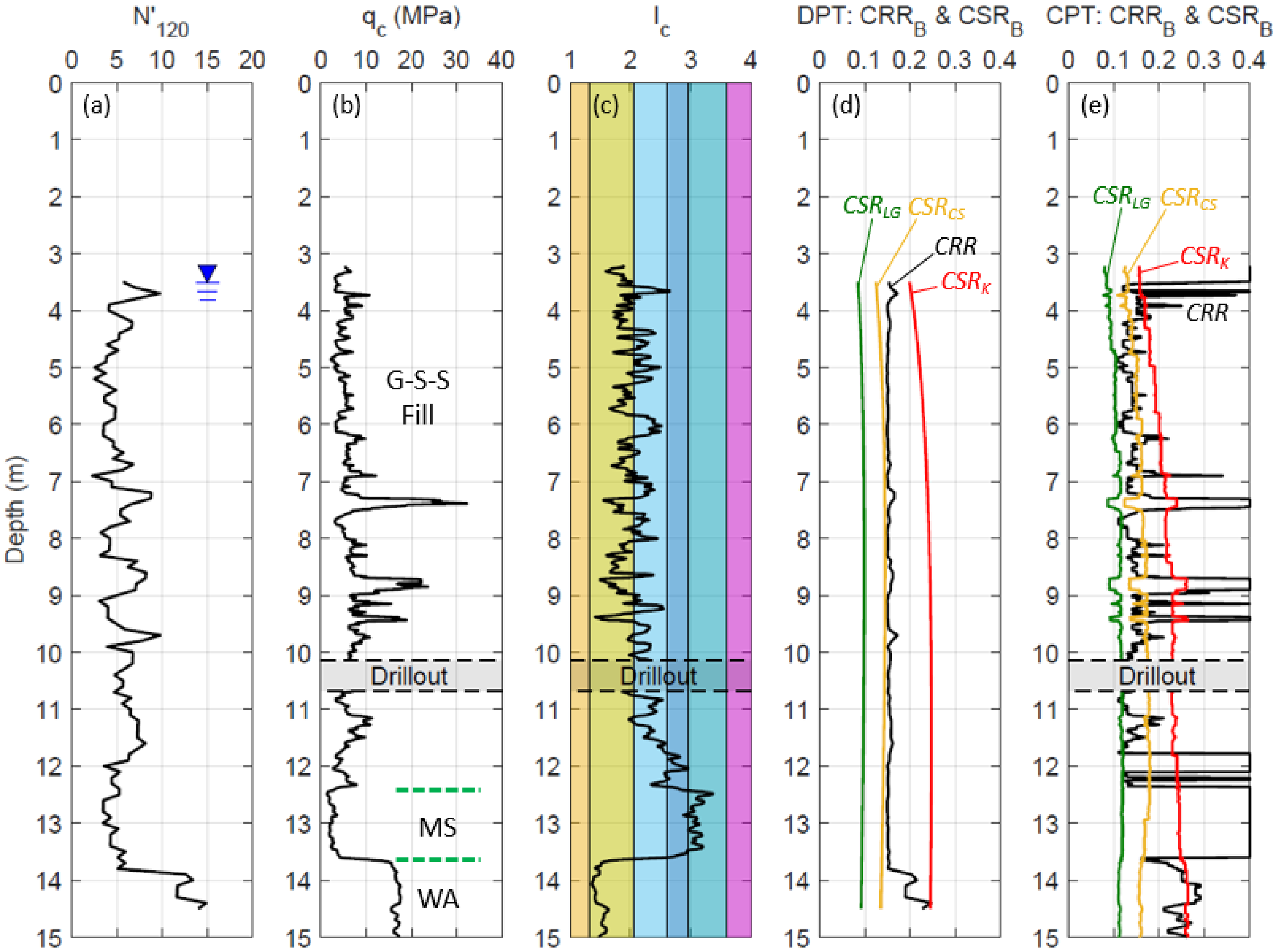

Figure 4. Profiles of (a) corrected DPT blow counts (N'_{120}), (b) CPT cone tip resistance (q_c), (c) CPT soil behaviour type index (I_c), and normalized cyclic resistance ratio (CRR_B) and cyclic stress ratio (CSR_B) calculated using (d) CPT-based and (e) DPT-based methods under the seismic demand of the Kaikōura (CSR_K), Cook Strait (CSR_{CS}) and Lake Grassmere (CSR_{LG}) earthquakes for a profile in the Thorndon G-S-S reclamation (DPT023 and CPT023). G-S-S denotes gravel-sand-silt, MS denotes marine sediments (with $I_c > 3$), and WA denotes Wellington alluvium.

4.3. V_s-Based Triggering Analysis

Results of the V_s-based triggering analysis are shown in Figure 5 based on data collected using cross-hole measurements between two boreholes located 3 m apart. Results from a CPT located approximately 9 m from one of the boreholes are also shown. Both tests were performed in the Thorndon reclamations that contain G-S-S fills, as indicated by the soil type descriptions in Figure 5b.

The G-S-S fill in the top 15.6 m depth have several different layers as identified by the CPT, including several 2–4 m layers of $I_c \approx 2.0$ and q_c = 5–10 MPa that are estimated to liquefy, separated by non-liquefiable layers of I_c = 2.5–2.8 (e.g., at 5.4–6.4 m depth). While there is some variation in V_{s1} within the G-S-S fill (mostly in the range of 210–300 m/s), the measured range of V_{s1} are larger than the case histories in the Kayen et al. (2013) liquefaction database and are therefore generally larger than the semi-empirical liquefaction triggering threshold of $V_{s1} \approx$ 220–225 m/s (Figure 3c). Hence, no liquefaction triggering is estimated to occur under any seismic demand, which is inconsistent with the CPT-based assessment results and observed seismic performance at CentrePort.

Only one small layer at 16.5–19 m depth contains data with V_{s1} < 210 m/s and therefore estimates CRR_B near the CSR_B induced by the Kaikōura earthquake. However, the CPT suggest this layer is likely to be the softer marine sediments, which are non-liquefiable by composition. Like in the DPT, the V_s-based assessment does not provide any insights on the soil behaviour type of the fill and hence does not allow for the determination of non-liquefiable soil layers without additional information from a borelog or laboratory test on soil samples collected at depth.

Compared to the CPT and DPT, the V_s-based assessment does not capture well the overall observed liquefaction performance of the CentrePort Thorndon G-S-S reclamations.

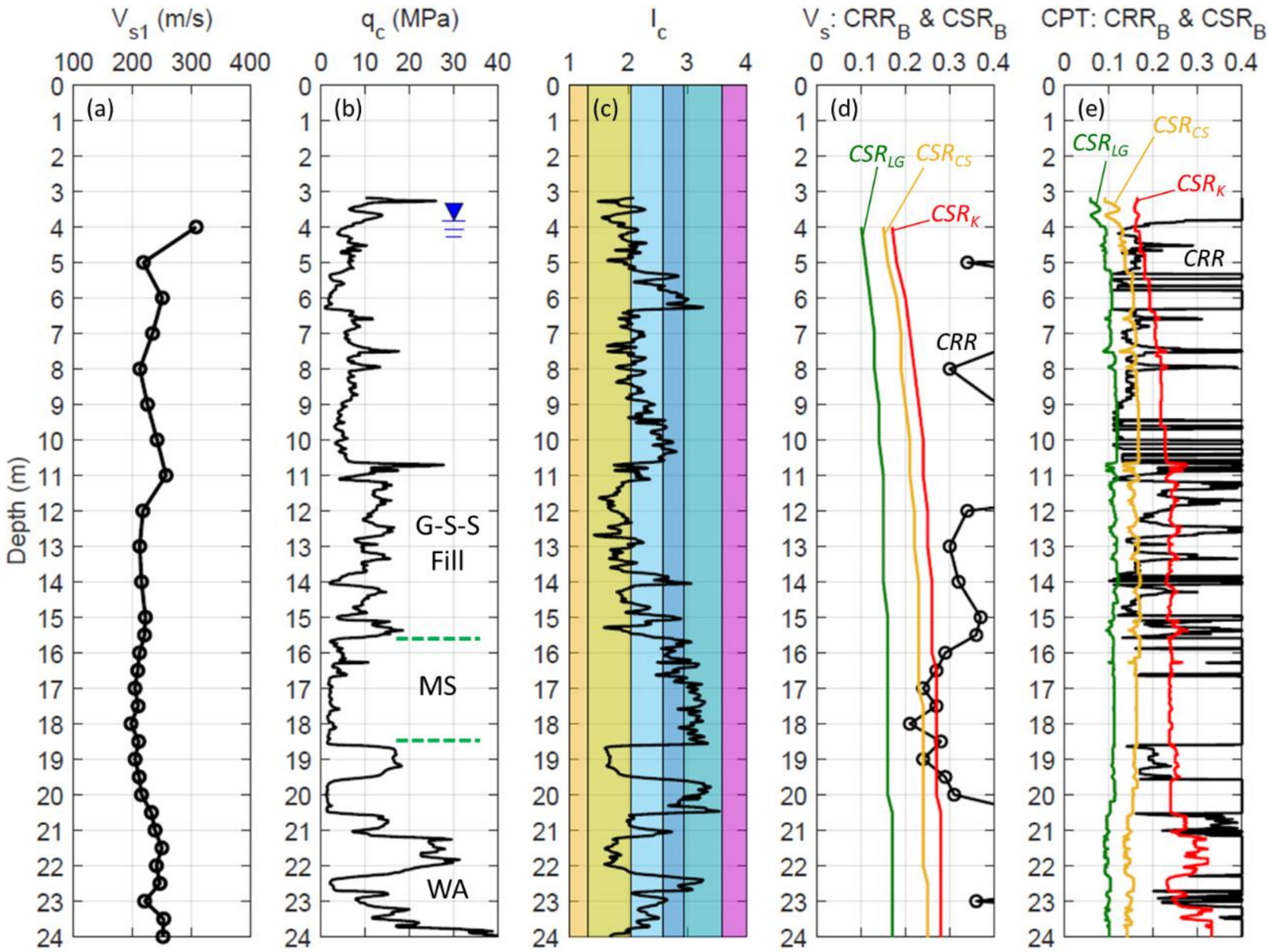

Figure 5. Profiles of (a) shear-wave velocity corrected for overburden stress (V_{s1}), (b) CPT cone tip resistance (q_c), (c) CPT soil behaviour type index (I_c), and normalized cyclic resistance ratio (CRR_B) and cyclic stress ratio (CSR_B) calculated using (d) CPT-based and (e) V_s-based methods under the seismic demand of the Kaikōura (CSR_K), Cook Strait (CSR_{CS}) and Lake Grassmere (CSR_{LG}) earthquakes for a profile in the Thorndon G-S-S reclamation (BH01 & BH02 and CPT039). G-S-S denotes gravel-sand-silt, MS denotes marine sediments (with $I_c > 3$), and WA denotes Wellington alluvium.

5. Conclusions

Liquefaction case histories of gravelly fills have an important similarity in that they typically contain 30–80% fine-to-medium gravels and 20–70% finer silty sand fractions, and hence are referred to as gravel-sand-silt (G-S-S) mixtures. This is an important feature as the finer sand and silt fractions tend to control the deformational response of the mixtures, resulting in the CPT and DPT exhibiting characteristics typical of silty sand (q_c = 4–10 MPa, I_c = 1.8–2.3, and q_{c1N} = 50–80 in the CPT, and N'_{120} = 4–7 in the DPT) for the well-documented case history of CentrePort.

Triggering assessment is performed using the DPT and V_s data in the CentrePort gravelly reclamations to check for consistencies and differences with the CPT-based triggering assessment. The DPT-based assessment results in similar outcomes as the CPT since the DPT also exhibits low penetration resistance that are characteristic of sands and silts, which govern the response of the G-S-S matrix. Like in the CPT-based assessment, the factor of safety values for the Kaikōura (~0.7) and Lake Grassmere (~1.5) earthquakes are in agreement with the observed performance, and the factor of safety is close to 1.0 for the Cook Strait earthquake (i.e., close to the triggering threshold). In contrast, the V_s-based assessment estimates no liquefaction for any earthquake event due to its large V_{s1} values (210–300 m/s) being above the liquefaction triggering threshold in the semi-empirical procedures. Hence, the V_s-based assessment does not capture well the observed liquefaction performance due to the relative insensitivity of the test to changes in the soil density and stratigraphy.

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