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Probabilistic Seismic-Induced Settlements at the Port of Long Beach Using CPT-Based Methods

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Abstract. Soil liquefaction is a main concern in geotechnical engineering that can potentially damage civil infrastructure, affect communities, and cause substantial economic losses. Numerous methods have been proposed to assess the risk of liquefaction triggering and have been successfully used to predict the onset of liquefaction. The main goal of this paper is to compare different methods used for the calculation of the factor of safety against liquefaction and liquefaction-induced settlements employing a probabilistic framework. The evaluation is mainly based on the results of Cone Penetration Test (CPT) probes of the Port of Long Beach (POLB), Pier S located in the southern California area. Although those methods are widely accepted and used in practice, this research presents a critical review of the methods used to calculate settlements and their large scatter when predicting earthquake-induced ground settlements.

Keywords. Risk and probability analysis, liquefaction, settlement, earthquakes, ports.

1. Introduction

Saturated loose sand deposits subjected to dynamic loading tend to accumulate excess pore water pressures leading to a reduction in effective stresses. This reduction causes loss of shear strength and stiffness. This phenomenon leads to an increase of the ground deformations and might cause damage to civil infrastructure [1], [2]. Idriss and Boulanger [3] discussed that the assessment of liquefaction susceptibility is best evaluated using several redundant procedures and its success depends on the quality of the field data, laboratory tests, and index tests used for soil characterization. One of the most reliable field tests used to evaluate liquefaction triggering is the Cone Penetration Test (CPT), which provides a continuous measurement of penetration resistance and friction of the soil. The results of CPT provide detailed definition of soil layers, which can be correlated to the liquefaction potential of subsurface soils. CPT-based liquefaction

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triggering methods supplement liquefaction susceptibility analyses performed with other methods based on Standard Penetration Tests (SPTs) or shear wave (Vs) velocities.

Liquefaction triggering of soils can be quantified using the factor of safety against liquefaction (FS_L), computed as the ratio of the liquefaction resistance of the soil over the cyclic shear stress demand induced by the earthquake. The Cyclic Stress Ratio (CSR) of a soil deposit is calculated from the peak horizontal acceleration at the ground surface induced by the earthquake, the total overburden pressure, the effective overburden pressure, and a stress reduction factor with depth [4]. The Cyclic Resistance Ratio (CRR) is generally estimated using empirical correlations determined using *in situ* testing. Several authors have proposed different liquefaction triggering methods for saturated sandy soils based on CPTs, including the procedures proposed by Robertson and Wride [5] as summarized by Youd et al. [6], Moss et al. [7], Idriss and Boulanger [8], Robertson [9] and Boulanger and Idriss [10].

Liquefaction can lead to volumetric strains in saturated granular deposits mainly arising from particle rearrangement, resedimentation, and dissipation of excess pore water pressure generated during the earthquake. Under free-field conditions, these strains cause ground surface settlement. Lee and Albaisa [11] and Yoshimi et al. [12] performed cyclic loading tests to study the volumetric strains and settlements in saturated sands arising from dissipation of excess pore water pressures. Later, Ishihara and Yoshimine [13] developed a method to obtain the volumetric shear strains generated during undrained cyclic loading. Idriss and Boulanger [8] presented a method to estimate liquefaction-induced settlements using the results of CPT.

The objective of this paper is to present an evaluation of the liquefaction potential and liquefaction-induced settlements at a site located at Port of Long Beach (POLB), Pier S, when subjected to an Operating Level Earthquake (OLE) condition with a peak ground acceleration (PGA) of $0.21g$ corresponding to an earthquake magnitude of 6.5, according to the POLB wide ground motion report by Earth Mechanics Inc. [14]. This evaluation is performed by comparing the results of several semi-empirical methods using CPT data collected in the port. Computed free-field ground surface settlements are related to the FS_L determined from the abovementioned approaches in a probabilistic framework [15].

2. Overview of semi-empirical methods

There are different methods currently used in geotechnical earthquake engineering practice to evaluate the liquefaction susceptibility of saturated sand deposits using CPT field tests. Among those methods are the semi-empirical procedures proposed by Robertson and Wride [5], Moss et al. [7], Idriss and Boulanger [8], Robertson [9], and Boulanger and Idriss [10]. Robertson and Wride [5] provided a curve to determine the CRR for clean sands based on the results of CPTs and normalized for an earthquake magnitude of 7.5. The soil behavior type index (I_c) presented in that method can be used to estimate the liquefaction resistance of soils; values lower than 2.6 indicate that the soil is susceptible to liquefaction. They included the correction for overburden stress (K_σ) proposed by Seed [16]. An updated version of this approach was proposed by Robertson [9] to include the behavior of clayey and silty soils subjected to seismic loadings. Even though clayey soil deposits are not susceptible to liquefaction, the method indirectly accounts for the contribution of the cyclic degradation of these soils in the computation of ground deformations. This update also included a modified stress exponent, which improved the soil response at large stress levels avoiding the use of the K_σ factor.

Idriss and Boulanger [8] proposed a method based on a comprehensive case history database. They introduced a fines content correction factor to the CPT-based CRR curve. Based on the results of CPT field tests, the authors introduced correlations to obtain K_σ and overburden correction (C_n) factors in terms of the cone penetration resistance for clean sands. A new magnitude scaling factor (*MSF*) was derived from laboratory test data using the CRR, number of cycles, and earthquake magnitude as input values. An update by Boulanger and Idriss [10] adjusted the CPT-based correlations after the extension of the case history database and thus, new MSF and C_n factors were proposed. The updated version included a new approach to estimate the fines content and soil classification based on the I_c index.

Moss et al. [7] compiled a database of CPT soundings including approximately 182 case histories and presented new correlations to assess soil liquefaction hazard using a normalization procedure for CPT resistance applicable to clean sands and silty soils. This normalization was made using a limit-state model to separate liquefiable from non-liquefiable soils and provided an improvement on the influence of effective overburden stresses on CPT measurements.

Liquefaction-induced settlements caused by volumetric strains and reconsolidation are also commonly estimated using semi-empirical methods. Ishihara and Yoshimine [13] correlated volumetric strains with relative density or corrected CPT tip resistance and the factor of safety against liquefaction. This approach showed that shear and volumetric strains increase when FS_L decreases. Maximum strain values are obtained for low values of relative densities. To quantify the liquefaction-induced ground settlements, Ishihara and Yoshimine [13] proposed the following procedure: i) determine the FS_L for each layer, ii) obtain the post-liquefaction volumetric strains using the cone penetration resistance and the FS_L as input values, and iii) estimate the settlements of each layer by multiplying the computed volumetric strain times the layer thickness. Idriss and Boulanger [8] based on the Ishihara and Yoshimine [13] relationships, proposed a method to estimate the vertical reconsolidation settlements of a sandy soil using, for example, the Robertson and Wride [5] CPT-based method to determine the FS_L.

All these procedures are widely used in current geotechnical practice to determine liquefaction susceptibility and liquefaction-induced settlements in free-field conditions. The results obtained from the calculation of liquefaction triggering and estimation of ground settlements using classical deterministic semi-empirical approaches may lead to large discrepancies among the different methods. Juang et al. [15] combined the deterministic methods for liquefaction triggering using the FS_L in a probabilistic framework derived from case histories to estimate the liquefaction-induced settlements and their probability of occurrence.

3. Subsurface conditions at The Port of Long Beach, Pier S

The POLB has been constructed on top of natural coastal and man-made land masses creating wide variations of ground conditions along the port area. Historically, some of the dredged materials have been used for the construction of man-made land masses currently present at the port. Figure 1 shows the results of ten CPT field tests in the Geotechnical Studies for Pier S Wharf Port of Long Beach [17]. The site is predominantly horizontal with some gently sloping ground. The average ground water level was estimated at elevation 1.8 m Mean Lower Low Water Level (MLLW) (i.e., water table at POLB). Unit A, a man-made compacted fill placed in the 2000s is composed of silty to clayey sands. It is located on top of marine/estuarine sediments (Unit B) that were also found to be loose and sandy in nature. Unit C is a dense lower marine/estuarine deposit composed of dense silty sands with thin layers of very stiff to hard silts. Then, Unit D is the Gaspur Formation composed of very dense medium to coarse grained sands with interbedded fine gravels. Each unit was subdivided in two zones to provide a better representation of tip (q_c) and sleeve (f_s) cone resistances of each soil layer. Figure 1 shows the results from the CPT soundings, average and maximum and minimum adopted values. Maximum and minimum lines are proposed by revising the I_c values to approximately fit the expected and observed soil behavior from soil boring logs. The minimum and maximum adopted lines in this paper are defined to approximately match average minus and plus one standard deviation data below and above average values.

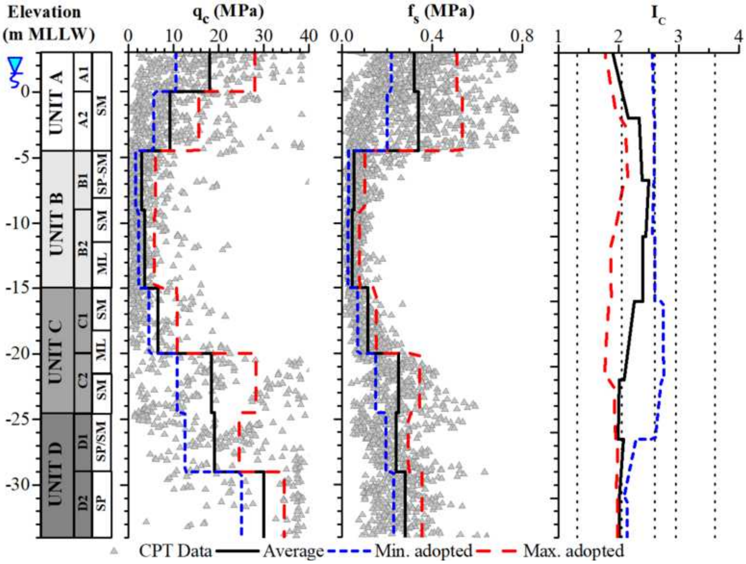

Figure 1. Subsurface conditions at the project site and CPT test bounds used in the analyses.

4. Factors of safety against liquefaction

The factor of safety against liquefaction was calculated for the average and minimum and maximum adopted lines from Figure 1 for each soil layer. Figure 2 shows variations of computed FS_L with depth obtained with the aforementioned CPT-based approaches. The calculations were performed for OLE conditions corresponding to an earthquake magnitude of 6.5 and a PGA of 0.21g. The CSR values of the soil deposit were calculated following each CPT approach. Slight variations of less than 15% were observed in the CSR calculations for each method. The CRR normalized for a 7.5 magnitude earthquake ($CRR_{7.5}$) was determined using the results of *in situ* CPT tests and the methods proposed by Robertson and Wride [5], Moss et al. [7], Idriss and Boulanger [8], Robertson [9] and Boulanger and Idriss [10].

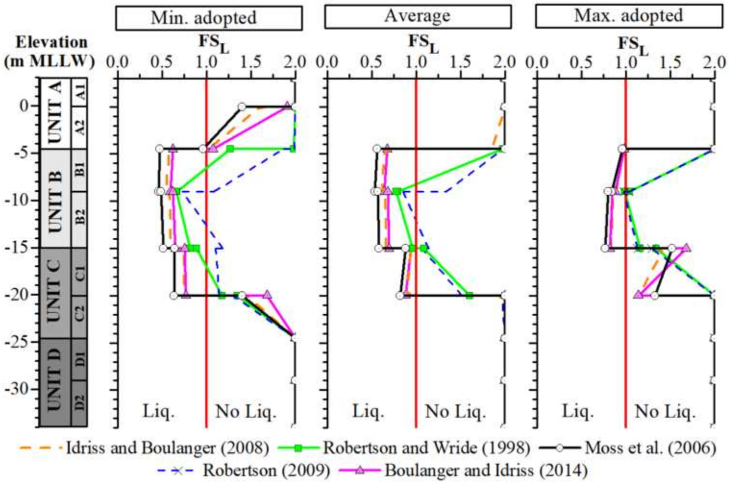

Figure 2. FS_L for the set of CPT data: average, maximum and minimum adopted.

Liquefaction analyses were performed up to an elevation of -20 MLLW, which corresponds to the transition between Units C2 and D1. Unit D corresponds to a non-liquefiable very dense granular soil deposit. For the assessment of the onset of liquefaction, the factor developed by Seed [16], denoted as K_α to account static shear stress conditions on the computation of the FS_L, was not applied. For liquefaction studies involving horizontal or gently sloped sites, this factor does not need to be included in the calculations. The results were verified with the program CLiq version 1.7.6.49 [18]. Regardless of the type of analysis used, computed FS_L was larger than one for Units A, D and for the most part of Unit C. Conversely, Unit B represents a liquefiable layer. Even though the methods evaluated in this paper lead to similar trends, some differences were computed among the semi-empirical methods in the calculation of the FS_L. For example, for the analysis using average values in Unit B, the factor of safety calculated with the Robertson and Wride [5] and the Moss et al. [7] approaches are approximately 0.75 and 0.55, respectively. Although the overall conclusion from both methods is the same, those differences will result in large discrepancies when assessing liquefaction-induced settlements and probability of liquefaction exceedance. For these type of subsurface and earthquake level conditions, slight differences were observed between the updated versions of the methods with respect to the original approaches (e.g., Robertson and Wride [5] and Robertson [9]).

Design recommendations should be made in light of liquefaction probability (P_L) as opposed to deterministic values and approaches. The abovementioned authors developed methodologies to calculate the P_L based mainly on the FS_L, cone resistance, CSR, CRR. Figure 3 shows the liquefaction probability curves computed from each CPT-based semi-empirical method presented in this paper. It is shown in the figure that the likelihood of liquefaction for Unit B is larger than that of any other soil layer. This is evidenced with computed liquefaction probabilities near 100%. Significant scatter in the results was computed using the methods evaluated in this paper. For example, for the average CPT data set, the probability of liquefaction varies between 50% and 100% in Unit B. These large differences are mostly attributed to discrepancies on the calculation of the FS_L.

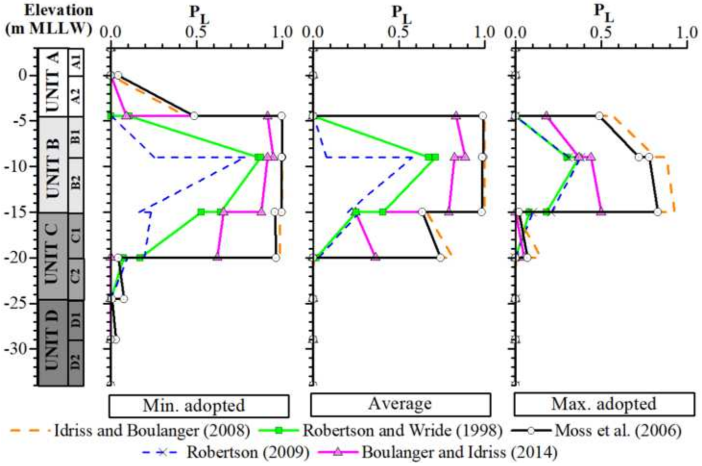

Figure 3. PL curves for each CPT data set: average, maximum and minimum adopted values (approximately equal to average plus and minus one standard deviation).

5. Liquefaction-induced settlement with semi-empirical methods

Soil liquefaction causes changes in the volumetric strains that result in ground surface settlement. Semi-empirical approaches were derived from case histories, mostly under free-field conditions. These methods are based on the computation of volumetric strains resulting from the earthquake that integrated over depth are used to compute ground settlement. Figure 4 shows the calculated liquefaction-induced settlements for free-field conditions using the approach proposed by Idriss and Boulanger [8]. Values are computed for OLE conditions using the set of CPT soundings summarized in Figure 1. The tip and sleeve cone resistance, and FS_L computed with the aforementioned CPT-based methods, are the required input values to compute settlements with the Idriss and Boulanger [8] method.

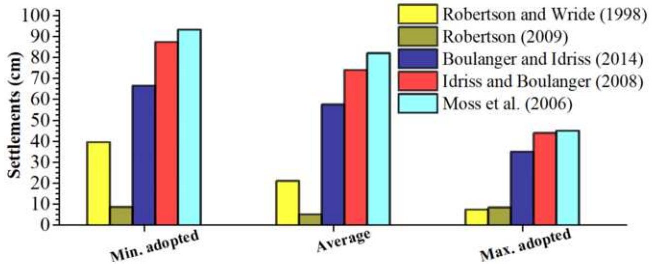

Figure 4. Computed ground settlements with classical semi-empirical approaches for OLE conditions with summarized CPT data.

Very large discrepancies in the results for the three-sets of CPT data summarized in this paper were observed with the method by Idriss and Boulanger [8]. For the average CPT values, variations from 5 to 82 cm of ground surface settlement were obtained with the Robertson [9] and Moss et al. [7] triggering models, respectively. These two methods showed the largest discrepancies on the computed results due to their differences in the calculation of the $\mathrm{FS_L}$. For the POLB Pier S, liquefaction-induced ground surface settlements for different PGA levels is also of interest. In addition to the Operational Level Earthquake (PGA of 0.21*g*), a larger Contingency Level Earthquake (CLE), with a PGA of 0.5*g* corresponding to a magnitude of 7.0 is also plausible according to the Port-Wide Ground Motion Study POLB [14]. The potential development of liquefaction-induced settlements is presented parametrically for different PGA values in Figure 5. The figure shows settlement versus PGA calculated with the method proposed by Idriss and Boulanger [8] using $\mathrm{FS_L}$ computed using Robertson and Wride [5], Moss et al. [7], Idriss and Boulanger [8], Robertson [9] and Boulanger and Idriss [10] methods. As discussed before, large differences between those methods were computed and the sensitivity of the Idriss and Boulanger [8] method to the $\mathrm{FS_L}$ input is evident. Regardless of the large scatter in the computed results, the figure shows large settlements as the PGA increases.

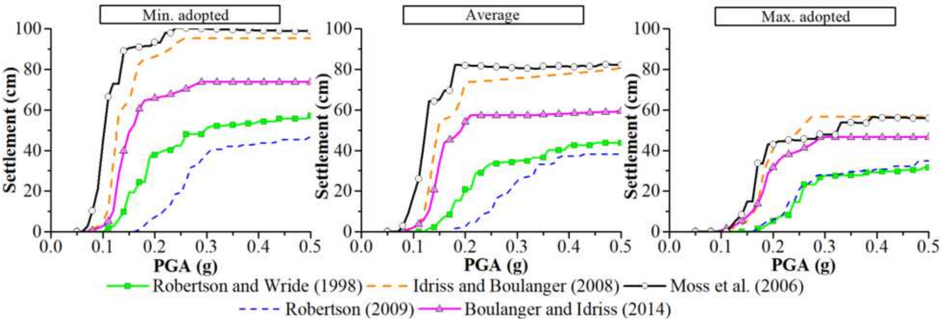

Figure 5. Computed ground settlement for different PGAs for each CPT data set: average, maximum and minimum adopted.

Juang et al. [15] proposed a probabilistic approach based on the settlements calculated from Idriss and Boulanger [8] and the CPT-based method of liquefaction susceptibility by Robertson and Wride [5]. This approach calculates the probability of exceedance of liquefaction-induced settlements. Figure 6 shows the results of this method for the set of CPT data presented herein. The lower the CPT resistances, the larger the liquefaction probability of exceedance. If the acceptable probability of exceedance is fixed to a relatively low value, for example to 15%, the liquefaction-induced settlements would vary from 15 to 35 cm for the average and minimum adopted CPT data sets. On the other hand, if one is willing to accept a larger risk, for example 50% probability of exceedance, the computed settlement would be less than 6 cm regardless of the CPT data set used in the analyses.

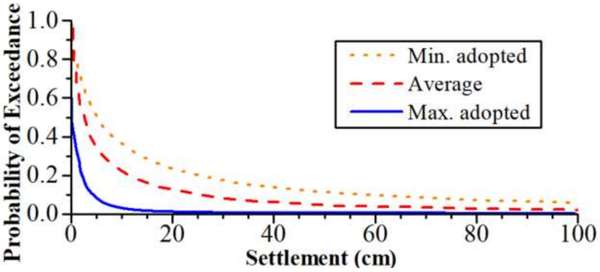

Figure 6. Probability of exceedance of settlement for each CPT data set adopted in this paper.

6. Conclusions

Large differences were computed in the calculation of *CRR*, *CSR*, and FS_L among the semi-empirical methods presented in this paper. Engineering judgement should be exercised to draw design recommendations regarding liquefaction susceptibility of soils. From the computed results and soil conditions, the most conservative method is the one proposed by Moss et al. [7]. The approach developed by Robertson and Wride [5] was more conservative than the updated version by Robertson [9]. The latest version by Boulanger and Idriss [10] was more conservative than the approach by Idriss and Boulanger [8]. The methods used to calculate liquefaction-induced settlements and liquefaction probability of exceedance were based on the calculation of the factor of safety against liquefaction and thus, were very sensitive to the selection of soil parameters. Numerical simulations using advanced constitutive soil models capable of capturing dynamic soil behavior are recommended to supplement the quantification of free-field liquefaction-induced settlements using the practical closed-form methods analyzed in this paper.

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