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RECENT ADVANCES IN ANALYSIS OF SEISMIC SETTLEMENTS

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Abstract

Earthquake-induced settlements caused by liquefaction and seismic compaction have the potential to induce significant damage to structures. Estimation of these settlements by practicing engineers is critical for seismic design of structures. However, due to the complexities and uncertainties associated with seismic events and the limited field data available for case histories of liquefaction and seismic compaction, earthquake-induced settlements are inherently difficult to estimate. Several methods are currently used in engineering practice for estimation of free-field seismic settlements in which large variations of estimated settlements are obtained. However, extensive research has been performed in recent years to further develop estimations of earthquake-induced settlements in the free-field and due to soil-structure interaction as well as to quantify the associated consequences to structures. Based on a comprehensive literature review, this paper compiles and discusses available methodologies and regulations for estimating seismic settlements, explores the trends of these latest advancements, and compares the results of estimated seismic settlements at a selected site profile. The goal of this paper is to provide practicing engineers and researchers with the state-of-the-art practice for estimating earthquake-induced settlements to understand current progress and limitations in the geotechnical earthquake engineering community.

Keywords: earthquake; seismic; settlement; liquefaction

1. Introduction

Several steps go into estimation of seismic settlements in practice. The first step is to assess the susceptibility of a soil layer to liquefaction or seismic compaction, and then to assess the “triggering” of liquefaction or seismic compaction occurring in a soil layer due to an earthquake load. Once it is evaluated that liquefaction or seismic compaction could occur, the next step is to estimate the soil deformations and displacements due to these phenomena and how they may affect the structure of interest. Over the past 50 or so years, liquefaction and seismic compaction have been extensively studied and the practice of analyzing these phenomena and their consequences has evolved.

Due to the several methodologies available for practitioners and the high variability of results, practicing engineers are often left to wonder which methodologies produce the best estimates and how does soil-structure interaction come into consideration. Significant progress has been made over more recent years in the understanding of the seismic settlement phenomenon, both in the free-field and with consideration of soil-structure interaction. This paper highlights a number of more recent methodologies that are used in practice today as well as some newer methodologies which consider soil-structure interaction that are more recently available and should be considered by practicing engineers. Once the methodologies have been reviewed and discussed, this paper presents a selected site profile using both Cone Penetrometer Test (CPT) data and compares the results of several selected methodologies.

2. Seismic Settlement Methodologies

Available methods to analyze liquefaction and seismic compaction and their resulting deformations vary dependent on the phenomena being analyzed and the site data being used. Methods vary based on whether the soil layer being analyzed is saturated (liquefiable) or unsaturated (susceptible to seismic compaction) and whether boring data or CPT data is available. Some methods are solely for analyzing the likelihood of liquefaction occurring and must be paired with another method to determine the associated deformations (such as settlement) that could occur. Furthermore, a majority of available methods are based on free-field measurements with more recent methods starting to consider soil-structure interaction.

In practice, settlements due to both liquefaction and seismic compaction are considered when analyzing potential seismic settlements and therefore several methods are used. Due to the uncertainty and limitations of these methods, often practitioners give a range or a “conservative” result. Furthermore, analyzing the surcharge loading from building foundations and other similar loads are often not considered in these more simplified methods and more appropriate, more expensive finite element modeling would be needed to consider soil-structure interaction.

Sections 2.1 and 2.2 discuss the various methodologies available for estimating free-field seismic liquefaction settlements and a discussion of the various methods used for seismic compaction and the details of each method is provided in Section 2.3. Furthermore, Section 2.4 provides a discussion of the methodologies available for estimating seismically induced building settlements.

2.1 Methods for Estimation of Seismically Liquefaction Induced Free-Field Settlements – CPT-Based Methods

2.1.1 Youd et al. 2001 (NCEER 2001)

The Youd et al. 2001 method [1], also referred to as the NCEER 2001 method, is a result of the 1996 National Center for Construction Education and Research (NCEER) and the 1998 NCEER/National Science Foundation (NSF) workshops on evaluation of liquefaction resistance of soils. This method, which is named after the Youd et al. summary paper of the workshops published in 2001, is still widely used in practice today and provides criteria for evaluation of liquefaction triggering of a saturated soil layer using CPT data. When analyzing standard penetration test (SPT) data, this method is often referred to as the NCEER 1997 method as discussed in Section 2.2.1 of this paper [2]. The Youd et al. 2001 summary paper also provides criteria for evaluation of liquefaction resistance based on lesser used field exploratory methods including shear wave velocity field measurements and Becker Penetration Test (BPT) data.

Although the Youd et al. 2001 [1] method is a simplified procedure, several steps are involved to execute this method with several equations and considerations for factors such as fine content correction and overburden stress correction. To summarize, this method generally involves the following steps: (1) evaluation of the cyclic stress ratio (CSR) based on seismic loading and soil stresses, (2) evaluation of the cyclic resistance ratio (CRR) based on CPT (or other) data, (3) calculation of the factor of safety against liquefaction based on the CSR and CRR, and (4) applying scaling factors to consider earthquake design magnitude, high overburden stresses, and static shear stresses to determine the final factor of safety against liquefaction. Theoretically, if the factor of safety against liquefaction (inclusive of scaling factors) is over 1.0, then liquefaction would not occur and hence no settlement induced by liquefaction. Some practitioners use safety factors higher than 1.0 to account for uncertainties in liquefaction evaluation or for more critical projects.

If the factor of safety against liquefaction is less than 1.0 using the Youd et al. 2001 [1] method, then it is assumed that the soil layer liquefies. However, this method does not provide any guidance on calculation of vertical settlements due to liquefaction. Therefore, this method is paired with other methods to estimate volumetric settlements based on calculated factor of safety, CSR, and other values. Methods that can be used in conjunction with Youd et al. 2001 include Zhang et al. 2002 [3] discussed in Section 2.1.6. The Zhang et al. 2002 procedure is the method that is implemented along with Youd et al. 2001 in the computer program CLiq [4] which is often used in practice.

2.1.2 Moss et al. 2006

The Moss et al. 2006 [5] method is a CPT-based, probabilistic liquefaction triggering assessment method. Settlements can be calculated by pairing this triggering method with another method for evaluation of volumetric strains. For instance, the software program CLiq [4] uses the Zhang et al. 2002 [3] method to calculate settlements in conjunction with the Moss et al. 2006 method.

The Moss et al 2006 method is an update to previous CPT-based liquefaction triggering potential assessment methods by using a larger database of liquefaction case histories. The main updates that were incorporated into this method include the normalization of CPT tip resistance, particularly for friction effects due to "apparent fines," and a revision to the CRR equation which is a function of user-specified probability of liquefaction and is often assumed to be 15 percent as recommended by Moss et al. 2006.

2.1.3 Idriss and Boulanger 2008

The Idriss and Boulanger 2008 [6] method is described in a comprehensive Earthquake Engineering Research Institute (EERI) Monograph and consists of correlations, equations, and charts for liquefaction triggering assessment and associated vertical settlements. The equations outlined in Idriss and Boulanger 2008 build on the CPT-based liquefaction triggering method outlined in Idriss and Boulanger 2004 [7], as discussed in Section 2.2.3 of this paper. Some improvements to the CPT-based procedure provided in Idriss and Boulanger 2008 include the inclusion of equivalent clean sands normalized tip resistance ($qc_{1N\text{-}cs}$) to be used in evaluation of CRR. The Idriss and Boulanger 2008 method also presents a method for estimation of volumetric settlements. It should be noted that the EERI monograph presents both SPT-based and CPT-based liquefaction triggering procedures, however, the SPT-based procedure presented in the monograph is the procedure outlined in Idriss and Boulanger 2004 and, therefore, this SPT-based procedure goes by that name.

This CPT-based method can be implemented within a spreadsheet or using computer software programs. The program CLiq [4] has the option to use the Idriss and Boulanger 2008 [6] method for analysis of both liquefaction triggering and volumetric settlements.

2.1.4 Robertson 2009 (Updated NCEER method)

The Robertson 2009 method is an update to the Robertson and Wride 1998 CPT-based liquefaction triggering assessment method based on an increase of case history data [8, 9]. The main updates included in the Robertson 2009 method include a revision for calculation of the normalized tip resistance value (q_{c1N}), which effectively voids the need for the overburden stress correction factor, as well as compilation of a set of equations based on Idriss and Boulanger 2004 [7] to expand evaluation of the CRR to all soils including clay-like soils [8]. This procedure also discusses identification of transition zones and considerations for these zones for liquefaction triggering analysis.

This method can be paired with another method for calculation of volumetric settlement and can be implemented in spreadsheets or analysis software. CLiq [4] incorporates this method paired with the Zhang et al 2002 [3] method for calculation of volumetric settlements.

2.1.5 Boulanger and Idriss 2014

Due to the increase of quantity and quality of liquefaction case histories, Boulanger and Idriss updated their SPT-based (Idriss and Boulanger 2004) and CPT-based (Idriss and Boulanger 2008) liquefaction triggering assessment methods in 2014. The main updates of the Idriss and Boulanger 2014 [10] CPT-based method include revisions to their CRR equation, magnitude scaling factor equations, and $q_{c1N\text{-}cs}$ equation. A recommended procedure for estimating fines content to be used in evaluation of $q_{c1N\text{-}cs}$ values was also presented. Furthermore, Boulanger and Idriss also presented a probabilistic CPT-based liquefaction triggering method in this publication.

This method can be paired with another method to estimate volumetric settlements and typically the Idriss and Boulanger 2008 [6] method is used for this. The Boulanger and Idriss 2014 [10] liquefaction triggering method can be implemented using spreadsheets or available computer programs. The program CLiq [4] includes this method along with the calculation of volumetric settlements per Idriss and Boulanger 2008 [6].

2.1.6 Zhang et al. 2002

The Zhang et al. 2002 [3] method is a CPT-based method that estimates volumetric settlements and is paired with a liquefaction triggering procedure. This method uses the factor of safety against liquefaction directly from a CPT-based liquefaction triggering procedure along with the equivalent clean sand normalized CPT tip resistance ($q_{c1N\text{-}cs}$) to estimate volumetric strains using a chart provided in the Zhang et al. 2002 paper. Settlement for a given layer is then calculated by multiplying the volumetric strain determined from the chart by the layer thickness and summing layer settlement across the soil profile.

The Zhang et al. 2002 [3] method can be implemented using spreadsheets and the chart, however, this method is also widely used in computer programs for CPT-based analysis. In the program CLiq [4], this method is implemented by default with three out of the five liquefaction triggering procedures available (Moss et al. 2006, Youd et al. 2001, and Robertson 2009) and can even be selected by the user to be implemented with the remaining two liquefaction triggering procedures if desired (Idriss and Boulanger 2008 and Boulanger and Idriss 2014).

2.2 Methods for Estimation of Seismically Liquefaction Induced Free-Field Settlements – SPT-Based Methods

2.2.1 NCEER 1997

The NCEER 1997 [2] method is result of the 1996 NCEER workshop and is a SPT-based method. The participants in the1996 NCEER workshop did not come to a consensus on CPT criteria for evaluation of liquefaction and, therefore, this method is only used for SPT-based analysis. As previously mentioned in Section 2.1.1, another NCEER workshop was held in 1998 and the Youd et al. 2001 [1] paper summarized the results of both the 1996 and 1998 workshops which also then recommended CPT-based procedures.

The NCEER 1997 [2] method uses a similar framework to the method laid out in Section 2.1.1 in which the CSR and CRR values are evaluated for a layer and the factor of safety against liquefaction is calculated. Scaling factors to consider earthquake design magnitude, high overburden stresses, and static shear stresses are also then applied to determine the final factor of safety against liquefaction. A notable result of the 1996 workshop for SPT-based liquefaction assessment is the introduction of correcting the $N_{1,60}$ value for clean sands ($N_{1,60\text{-}cs}$) and using the $N_{1,60\text{-}cs}$ value for evaluation of the CRR.

As this method is a liquefaction triggering analysis method, the NCEER 1997 [2] method must be coupled with a volumetric settlement procedure to estimate vertical settlements of a soil profile. Spreadsheets programmed with equations from the NCEER 1997 paper can be used to implement this SPT-based method. As this method is still widely used in practice today, the NCEER 1997 liquefaction triggering method is also available from computer programs which analyze liquefaction resistance including CLiq, LiquefyPro, and Settle3D [4, 11, 12].

2.2.2 Seed et al. 2003

The Seed et al. 2003 [13] paper presents a new probabilistic procedure for assessment of liquefaction triggering potential based on new correlations by Cetin and Seed [14] and Cetin et al. [15]. The new procedure was developed based on an expanded database of case histories, improved interpretation of SPT data, a new method for analyzing CSR, and an improved understanding of ground motions and probabilistic based procedures.

This updated procedure presents new correlations for analysis of probability of liquefaction occurring based on the $N_{1,60\text{-}cs}$ value and normalized CSR value for a specific overburden stress. Calculation of the CSR value is updated based on improvements to calculations of the shear stress reduction coefficient (r_d) which is used in the equation for calculation of CSR.

The Seed et al. 2003 [13] procedure is a liquefaction triggering method only and needs to be coupled with another procedure for estimation of volumetric settlements. This procedure can be implemented in spreadsheets but is also generally available in liquefaction analysis programs including CLiq [4].

2.2.3 Idriss and Boulanger 2004

The Idriss and Boulanger 2004 [7] method is a SPT-based semi-empirical method for assessing liquefaction triggering potential. This method is similar to the Youd et al. 2001 [1] method using the CSR and CRR and scaling factors to consider factors such as earthquake magnitude with updates to the equations used for consideration of these factors. Updated equations are presented for the r_d value used in calculation of CSR, the magnitude scaling factor, the factor for high overburden stresses, and the overburden normalization factor used in correcting SPT N-values.

Although the updated equations apply for CPT-based liquefaction triggering assessment as shown in Idriss and Boulanger 2004 [7], an updated CPT-based method was presented in Idriss and Boulanger's 2008 EERI Monograph [6] and, therefore, the CPT-based method goes by this name and uses the 2008 procedure as discussed in Section 2.1.3 of this paper.

The Idriss and Boulanger 2004 [7] SPT-based method can be implemented using spreadsheets or using liquefaction analysis software, such as CLiq and Settle3D [4, 12], and settlements can be calculated by pairing this method with another method for calculation of volumetric strains.

2.2.4 Boulanger and Idriss 2014

As discussed in Section 2.1.5 of this paper, the Boulanger and Idriss 2014 [10] paper provides an update to their previous SPT and CPT-based procedures due to an increase in available case history data. The main update of the SPT-based model consists of a revision to the magnitude scaling factor equations.

The SPT-based Boulanger and Idriss 2014 [10] method can be implemented using spreadsheets and is also available on CLiq. As this is a liquefaction triggering method, this method needs to be coupled with another method for calculation of volumetric settlements and typically the Idriss and Boulanger 2008 [6] method is used.

2.2.5 Tokimatsu and Seed 1987

The Tokimatsu and Seed 1978 [16] method is still often paired with other liquefaction triggering procedures to estimate vertical settlements. This procedure is also a widely used method today for estimation of seismic compaction settlements of dry, clean sands. This methodology involves a step-by-step process requiring the use of charts and tables for determination of settlement of a given soil layer.

The Tokimatsu and Seed 1978 [16] procedure involves a basic six step process starting with (1) estimating the cyclic shear stress and shear modulus (G_{max}) from boring and seismological data using published correlations, (2) using the cyclic shear stress and G_{max} to calculate the shear strain to shear modulus ratio, (3) using a chart and the shear strain-shear modulus ratio to estimate the effective shear strain, and then (4) using another chart and the effective shear strain to estimate the volumetric strain. Step (5) involves the correction to the estimated volumetric strain for magnitude and step (6) consists of calculation of settlements using the magnitude-corrected volumetric strain and layer thickness and accounting for a factor of 2 to consider multi-directional shaking.

The Tokimatsu and Seed 1978 [16] method can be implemented using spreadsheets and the charts provided in their paper and it is also implemented in the computer program LiquefyPro [11] for calculation of both saturated and dry soil settlement. It should be noted that this procedure could be extended to CPT data by converting the cone resistance data for a layer to SPT $N_{1,60}$ data and using the $N_{1,60}$ values for calculation of G_{max} as is done in LiquefyPro. Furthermore, Robertson 2009 [8] provides correlations between G_{max} and CPT tip resistance that could be used as well.

2.2.6 Ishihara and Yoshimine 1992

Like the Tokimatsu and Seed procedure, the Ishihara and Yoshimine 1992 [17] procedure is paired with a liquefaction triggering method in order to estimate vertical settlements. Corrected N-values values from boring data are converted to relative density and the relative density is used along with the factor of safety against liquefaction from the selected liquefaction triggering procedure. The volumetric strain for a given layer is calculated using a chart in the Ishihara and Yoshimine 1992 paper using the factor of safety against liquefaction and relative density. The volumetric strain is then multiplied by the layer thickness to provide the estimated vertical settlement for that layer.

The Ishihara and Yoshimine 1992 [17] method can be implemented using spreadsheets and the charts provided in their paper. This method is also available in various liquefaction analysis computer programs including LiquefyPro [11]. It should be noted that this procedure can also be extended to CPT data by converting corrected tip resistance values to corrected N-values and then converting to relative density.

2.3 Methods for Estimation of Seismic Compaction Settlements

2.3.1 Tokimatsu and Seed 1987

The Tokimatsu and Seed 1987 [16] method was previously described in Section 2.2.5 of this report as a procedure that can be used on conjunction with a liquefaction triggering procedure to estimate liquefaction induced settlements. However, this procedure is also a widely used method today for estimation of seismic compaction settlements of dry, clean sands as well. As previously mentioned, the Tokimatsu and Seed 1978 method can be implemented using spreadsheets and the charts provided in their paper and it is also implemented in the computer program LiquefyPro [11] for calculation of dry soil settlement.

2.3.2 Pradel 1998

The Pradel 1998 [18] method is a modification of the Tokimatsu and Seed 1978 [16] method for dry, clean sands using boring data. The same basic steps are used for the Pradel 1998 method as was described in Section 2.2.5, but the main difference between the Pradel 1998 and the Tokimatsu and Seed 1978 method is that Pradel provides a set of equations that can be used and implemented directly to estimate the volumetric settlement of a dry sand layer subjected to seismic loads and accounting for multi-directional shaking. This method can be implemented using spreadsheets that use these equations and is also implemented in the computer program Settle3D [12].

2.3.3 Robertson and Shao 2010

The Robertson and Shao 2010 [19] method is a modification to the SPT-based method by Pradel 1998 [18] that can be used with CPT data and is also reportedly suitable for a wider range of soils. The modifications for the method primarily are seen when determining G_{max}, which is estimated using the Robertson 2009 [8] correlation, and when calculating volumetric strains, which suggests using a modified correlation based on Lunne et al. 1997 [20] between CPT clean sand equivalent penetration resistance and SPT $N_{1,60}$ in order to use the equation for volumetric strain presented by Pradel 1998. Settle3D [12] also implements this method for CPT-based analysis.

2.3.4 Ghayoomi et al. 2013

The Ghayoomi et al. 2013 [21] paper presents an empirical methodology for free-field seismic settlements for partially saturated sand validated against centrifuge testing which maintained a uniform degree of saturation within the tested sand layer. As this method is presented for layers which are partially saturated, this method is not for assessment of liquefaction triggering for layers below the groundwater table.

Similar to other procedures for estimation of seismic settlement, the empirical relationship presented by Ghayoomi 2013 [21] considers the volumetric strain of a soil layer and the total settlement is the summation of the volumetric strains multiplied by their respective layer thicknesses. The volumetric strain of the partially saturated soil layer is presented to be the sum of the volumetric strain due to compression of air-filled voids and the volumetric strain due to reconsolidation associated with the dissipation of excess pore water pressure from water-filled voids.

The equation for estimation of volumetric strain due to compression presented by Ghayoomi 2013 [21] considers the effective shear strain, earthquake magnitude, and relative density of the soil layer as does other methods; however, the degree of saturation is also considered. Additionally, the equation for estimation of volumetric strain due to reconsolidation presented by Ghayoomi 2013 considers similar parameters including the degree of saturation in which the degree of saturation is taken into account with the parameter r_u corresponding to the ratio of excess pore water pressure to initial effective stress.

Although the Ghayoomi 2013 [21] method provides insightful conclusions with regards to the assessment of partially saturated sands, the empirical relationships presented seem to under estimate settlements in mid-ranges of saturation. Furthermore, partial saturation is often hard to define in field studies and is generally not consistent over a soil layer further complicating the use of this methodology and validation using case studies. However, the use of centrifuge testing for validation of empirical methodologies for partially saturated sand provides guidance for further research development.

2.4 Methods for Estimation of Seismically Induced Building Settlements

2.4.1 Bray and Macedo 2017

The Bray and Macedo 2017 [22] method is a relatively new method which attempts to provide a simplified approach for estimating liquefaction-induced settlements accounting for the building or structure interaction. This approach sums the liquefaction ejecta-induced settlement, volumetric-induced settlement, and shear-induced settlement to estimate a total liquefaction-induced building settlement. The ejecta-induced and volumetric settlements are estimated using other methods, such as the Ballegooy et al. 2014 [23] Liquefaction Severity Number method for ejecta-induced settlements and Zhang et al. 2002 [3] with a liquefaction triggering method for the volumetric-induced settlements. The Bray and Macedo 2017 method provides the shear-induced liquefaction settlements.

The shear-induced liquefaction settlement, as estimated by Bray and Macedo 2017 [22], is calculated using an equation which is a function of the Liquefaction Building Settlement Index (LBS), height of the liquefaction layer(s), building contact pressure, width of the building foundation, the 5-percent damped spectral acceleration period at one second (Sa_1), and the standardized cumulative absolute velocity (CAV_{dp}). The CAV_{dp} can be estimated using the procedure outlined by Campbell and Bozorgnia [24].

Bray and Macedo have provided a spreadsheet with the publication of this method which performs the calculation of the shear-induced liquefaction settlement based on user-provided input data. This spreadsheet also includes the Campbell and Bozorgnia 2011 [24] method to calculate the CAV_{dp} parameter. Other input parameters are relatively simple to estimate based on the building configuration and loading and the site's seismic setting; however, the LBS index is calculated based on an integral equation that is a function of the volumetric-induced shear strain. Bray and Macedo's method [22] has been implemented in CLiq [4] and, therefore, this program calculates LBS as a function of the CPT data and associated volumetric shear strains. With the input of the other parameters, the program also calculates the shear-induced liquefaction settlement. If only SPT data is available for a site, LBS can also be estimated using the volumetric shear strains from a liquefaction triggering and volumetric settlement analysis with the SPT data.

2.4.2 Bullock et al. 2019

The newer Bullock et al. 2019 [25, 26] model also attempts to account for soil-structure interaction by using the CAV parameter to estimate total building settlements (i.e. volumetric and shear strains). This semi-empirical probabilistic model uses ground motion prediction equations (GMPEs) developed by Bullock et al. 2017 [27] for estimation of CAV. The CAV parameter, along with other seismological input parameters, including earthquake magnitude, rupture depth, tectonic environment, focal depth, and rupture mechanism, is used with foundation and building information and soil profile information to calculate the probability of exceeding a settlement threshold. The soil profile information needed for this analysis is SPT or CPT-based and includes the $N_{1,60}$ value or q_{c1N} value and the depths to the top and bottom of the soil layer. It should be noted that penetration data is not corrected for clean sands as laboratory data information for validation of this model was too sparse to incorporate this standardization.

The foundation and building information required to perform the Bullock et al. 2019 [25, 26] analysis consists of the foundation width and length, embedment depth, bearing pressure, and the building height and mass. Due to the extensive information needed on the building and the model framework for a mat foundation, this model has limitations as often this type of detailed information is not available when performing liquefaction analyses and/or mat foundations aren't as commonly used. Furthermore, validation of the results presented in the Bullock et al. 2019 paper concluded that this procedure captures shear-induced strains well but that volumetric strains were often slightly underestimated.

The Bullock et al. 2019 [25, 26] model also calculates the probabilistic building tilt in degrees which is a failure mechanism often seen in case histories. Although there are some limitations to this procedure, the Bullock et al. 2019 model is a significant step into providing a performance-based framework for all seismic analysis and can be implemented using an available spreadsheet authored by Dr. Zachary Bullock and Dr. Shideh Dashti.

2.4.3 Tokimatsu 2019

Dr. Tokimatsu recently published a new, simplified procedure for estimation of building settlements due to liquefaction for a shallow rigid foundation based on a series of controlled centrifuge tests [28]. This method estimates the index for liquefaction-induced relative building settlement (I_{LBS}) (in units of length) based on the following parameters: foundation contact pressure, foundation width and length, depth from the ground surface to the bottom of the soil layer, and degraded deformation modulus and Poisson's ratio of the soil layer. The simplified method also uses a constant variable which accounts for converting the settlement calculated at the corner of a flexible foundation into an average settlement of a rigid foundation. Tokimatsu 2019 [28] also presented a simplified equation for assessing building tilt due to liquefaction using I_{LBS} and the foundation width.

Limitations to this new procedure are present due to the fact that the methodology presented by Tokimatsu 2019 [28] is for a rigid mat foundation and likely would not correlate well with shallow spread or strip footings. Furthermore, this method is based solely on centrifuge testing and field verification with case histories are needed to confirm the use of this method in engineering practice. However, for rough estimations of building settlement and building tilt due to liquefaction, this method could be implemented within spreadsheets.

3. Comparison of Liquefaction Methodologies Using a Site Profile

Using some of the methodologies summarized in Section 2, an analysis was performed with the goal of comparison of liquefaction-induced settlements. This analysis utilized the commercially available software program CLiq [4] for analysis of CPT-based methods. SPT-based methods were not considered in this comparison as current engineering standards are increasingly relying on CPT-based methods due to the continuous data that the CPT provides. The analysis was performed for comparison and informational purposes only.

Fig. 1 and Fig. 2 present the estimated settlements from four CPT tests performed within relatively short distances from each other in similar subsurface conditions. We used five different liquefaction triggering procedures in CLiq, as shown in Fig. 1 and Fig. 2, coupled with two different volumetric settlement methods for liquefaction and one volumetric settlement method for seismic compaction of the soils above the groundwater table. These triggering procedures consisted of NCEER 2001 (herein referred to as the Youd et al. 2001 method), Robertson 2009, Idriss and Boulanger 2008, Moss et al. 2006, and Boulanger and Idriss 2014. The Idriss and Boulanger 2008 and Boulanger and Idriss 2014 triggering methods used the Idriss and Boulanger 2008 method for calculation of volumetric settlements while the remaining three triggering methods used the Zhang et al. 2002 method for calculation of volumetric settlements. All methods used the Robertson and Shao 2010 method for calculation of seismic compaction settlements.

As shown in Fig. 1, the settlements estimated using Idriss and Boulanger 2008 and Boulanger and Idriss 2014 are relatively significantly larger than those estimated by the other procedures. These results change, however, if using the probability of liquefaction to estimate volumetric strains as can be selected in CLiq. Fig. 2 shows the comparison of estimated settlements using the five different procedures using probability of liquefaction based volumetric strains. As defined in CLiq's user manual [4], when the user selects to use the "PL based volumetric strains" option, then the settlements are estimated at each CPT data point using the calculated volumetric strain multiplied by the estimated probability of liquefaction. For this case, all five procedures show comparable estimates.

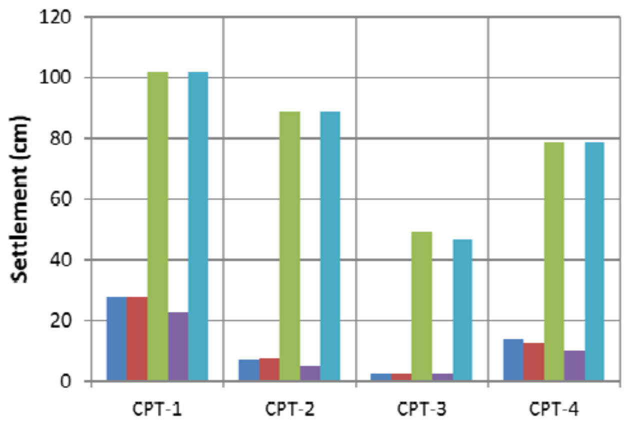

Fig. 1 – Comparison of CPT-Based Estimated Settlements from CLiq

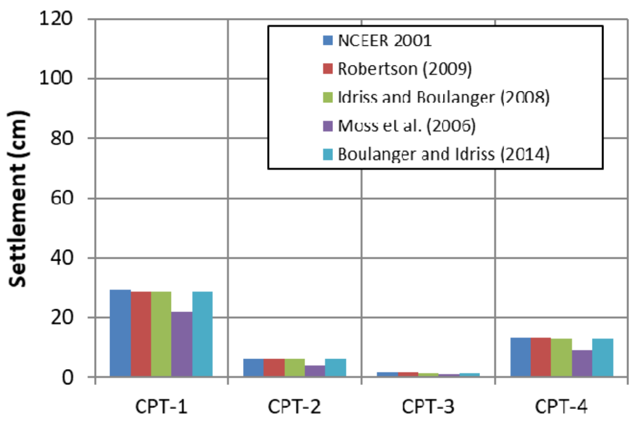

Fig. 2 – Comparison of Estimated Settlements Using Probability of Liquefaction Based Volumetric Strains from CLiq

An analysis was also performed to compare the results of the methods which consider the building interaction using readily available spreadsheets. Excel spreadsheets were provided by the authors for the Bray and Macedo 2017 and Bullock et al. 2019 procedures. As mentioned in Section 2.4, the Bullock et al. 2019 procedure directly estimates volumetric and shear strains to provide a total building settlement while the Bray and Macedo 2017 method only computes shear-induced settlements and must be added to the volumetric settlement estimated from a free-field method. For the purposes of this comparison, ejecta-induced settlements were ignored.

The analysis assumed the same arbitrary yet reasonable parameters for a mat foundation system including the foundation width, length, embedment depth, and contact pressure. Furthermore, seismic parameters were also assumed and both methods used consistent parameters. Lastly, as the probability of liquefaction occurring is typically defined as 15 percent for several free-field liquefaction triggering methods and since both the Bray and Macedo 2017 and Bullock et al 2019 procedures present results probabilistically, the 84^{th} percentile amount of settlements (i.e. one standard deviation above the median or a probability of exceedance of 16 percent) were used for consistency with free-field liquefaction triggering procedures.

Using the assumed parameters and the CPT data for CPT-1, the Bray and Macedo 2017 method estimated median shear-induced settlements of approximately 5 cm. Adding the shear-induced settlement to the average volumetric settlement across the five procedures shown in Fig. 2, the total volumetric and shear settlement was estimated to be approximately 32 cm. This result is relatively close to the 84^{th} percentile volumetric and shear-induced settlement of approximately 29 cm estimated using the Bullock et al. 2019 method.

The change in the amount of settlements estimated as a function of the probability of exceedance using the Bullock et al. 2019 procedure is illustrated in Fig. 3. As the Bray and Macedo 2017 method needs to be added to a method which estimates volumetric settlements, probabilistic trends are not plotted and only the 84th percentile settlement is plotted.

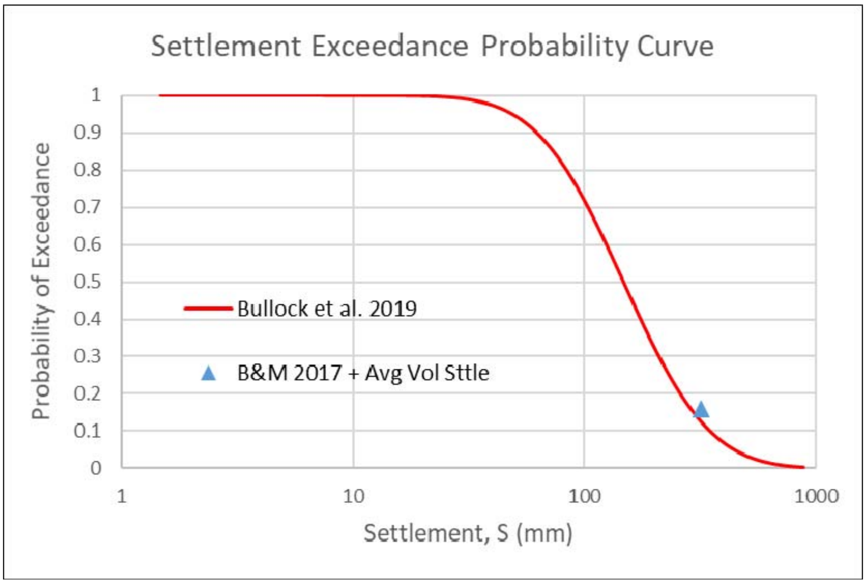

Fig. 3 – Settlement Exceedance Probability Curve for Building Settlements

4. Conclusions

As presented in this paper, there are several procedures available for estimation of settlements associated with liquefaction and seismic compaction with some procedures commercially available in current engineering software programs. Due to the variety of the framework associated with each method, it is important in engineering practice to perform multiple procedures for a better understanding of the potential seismic settlement hazard that may be present at a given site and to exercise engineering judgement to apply only the procedures applicable to site-specific conditions. Furthermore, comparison of some of the CPT-based liquefaction triggering and settlement procedures has shown that using probabilistic-based methods provides a relatively good agreement.

Although SPT-based methods were not compared within the site profile presented in Section 3, Section 2.2 of this paper provides several SPT-based methods that are currently used in practice today. However, due to the continuity of the CPT test and the type of data that is obtained, current standards are recognizing that analyses of seismic settlement using SPT data would benefit from being supplemented with CPT data if possible.

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