Evaluation of Vibro-Compaction for Liquefaction Mitigation by CPTu-based state characterization

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ABSTRACT: Vibro-compaction has been considered as an efficient method for soil improvement and mitigation of the liquefaction potential in loose saturated sands. Because of the relatively lower costs, simplicity of operation, the continuous measurement with depth, and the high accuracy and the repeatability, piezocone penetration testing (CPTu) is becoming the most applicable in situ test in geotechnical engineering for evaluating of liquefaction potential. In this study, a self-developed deep vibratory probe compaction equipment with frequency-variable piling vibrator used for Suqian-Xinyi Expressway project, a liquefiable site in China is introduced. Field tests including CPTu were performed before and after ground treatment. Four CPTu-based criteria have been used including corrected cone tip resistance (q_t) variations before and after modification, Q_{tn} and q_{c1N}, soil behavior classification charts, and state parameter methods. The results showed that due to vibro-compaction the state of soil changed from loose to dense, the volume change behavior of sands changed to dilative, and the liquefaction potential were also diminished. It was also observed that improved soils were not in the contractive(loose) zone anymore based on soil behavior classification charts. Therefore, it is concluded that CPTu is an effective way to evaluate the liquefaction mitigation effect of vibro-compaction.

Keywords: Piezocone penetration testing (CPTu); ground improvement; soil behavior classification charts; state parameter

1. Introduction

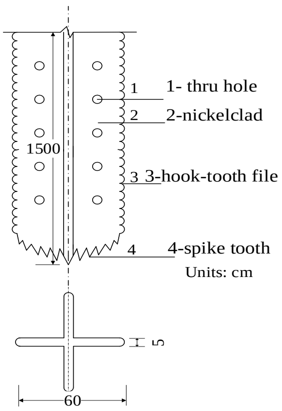
Soil liquefaction is the most common and destructive causes of damage and loss in loose saturated sandy deposits [1]. Vibro-compaction is a ground improvement technique of deep densification of granular soils using wave generated from a vibratory probe. Under the influence of vibration, the state of soil changed from loose state to more compacted state. Thus, vibro-compaction is frequently used for reducing or eliminating the liquefaction risk and improving not only soil properties but also overall seismic performance [2]. An understanding of the variability of soil state, properties and liquefaction potential before and after soil improvement are the main concern of the foundation treatment and liquefaction mitigation.

Cone penetration testing (CPT) or Piezocone penetration testing (CPTu) is a common method for monitoring and evaluating the performance of vibro-compaction improvement using its continuous records before and after vibro-compaction [3-5].

The principle objective of this paper is to investigate the effects of vibro-compaction on liquefaction mitigation using CPTu data. The following criteria: q_t, Q_{tn} and q_{c1N} variations pre and post vibro-compaction; two commonly used soil behavior classification charts and state parameter methods were used.

2. Self-developed vibratory probe compaction method

The compaction equipment consists of a vibrator with powerpack, a cross-shaped vibro-wing and a carrier machine in as shown in Fig.1 (a). The cross-shaped vibration wing is a cylindrical probe including two perpendicular steel plates as shown in Fig.1 (b). The vibrator has variable operating frequency between 0 and 20 Hz based on an electronic control system. The operating frequency of the vibrator is adjustable with the resonance frequency of the vibrator–probe–soil system to create the vibration amplification effect in practice and the optimal operating frequency is 17Hz. The vibro-wing penetrates and raises at a rate of 2.0 m/min and 1.2 m/min, respectively.



(a)

(b)

Figure 1. The cross-shaped vibration equipment:(a) crisscross section vibratory probe(b) equipment machine in field tests

3. CPT-based evaluation of liquefaction

To evaluate the liquefaction potential for liquefiable ground, it is important to know the soil stratigraphy and in situ soil state. CPTu has been widely used for geotechnical site characterization due to its high accuracy and repeatability. The CPT/CPTu has become the most-common in situ testing method for site investigation, especially for soil compaction projects [5]. Many researchers have suggested different classification for soil behavior by q_c measurement. The state of soil (loose, medium, and dense) can be distinguished based on q_c value. In this study, CPTu records before and after ground treatments were used to evaluate the performance of vibro-compaction.

3.1. Q_{tn} and q_{c1N} criteria

The factors influencing dilatancy behavior of sand are grain size, density, and confining pressure. It is well expected that these factors also affect cone tip resistance, q_t. The border between dilatant and compressive behavior can be using the following equation based on CPT test results [6].

$$Q_{tn} = q_t / (\sigma'_V)^{0.65} \quad (1)$$

where Q_{tn} is normal cone tip resistance, q_t is the the total cone resistance corrected for unequalend-area ratio and pore pressure effects(kPa), σ'_V is effective vertical stress(kPa).

Sladen and Hewitt[6] studied the influence of in situ density of hydraulic sand fills. The results given that for sands with Q_{tn} more than 70, the soil is considered dense and has dilation behavior; for soil with Q_{tn} less than 70, the soil is considered loose and will show compression behavior. Campanella and Kokan[7]studied the new approach to measuring dilatancy based on the resistivity piezocone penetration testing (RCPTU) results in different cases and suggested that a mean value of Q_{tn}=55 for the boundary between contractive and dilative behavior (i.e., the sands with Q_{tn} less than 55 are considered loose or contractive) . Therefore, the criterion should be check to any type of sand as diltancy is also affected by some factors of mineralogy, age, and so on.

Normalized cone tip resistance can be also correlated well to in situ relative density, which makes it used for state characterization[7]. Robertson [8] proposed an boundary line between contractive and dilative based on the equivalent clean sand normalized cone resistance, $(q_{c1N})_{cs}$ and suggested the value of $(q_{c1N})_{cs}$ is 75 as the border between loose and dense sands (i.e., sands with $(q_{c1N})_{cs}$ more than 75 are considered dense or dilative). The $(q_{c1N})_{cs}$ can be calculated by the following equation.

$$(q_{c1N})_{cs} = K_c \cdot (q_{c1N}) \quad (2)$$

where q_{c1N} is normalized cone resistance (dimensionless), K_c is a correction factor. The detailed calculation can refer to [8].

3.2. Soil behavior classification charts

Since, the CPTu can be able to provide continuous soil profiling readings including cone resistance (q_t), sleeve friction (f_s), and corrected pore pressure in cone tip (u_2), all these readings are functions of soil type and behavior[9]. Therefore, it can be used for soil type identification based on these readings[10-11]. Soil behavior classification charts have been used for a better assessment of soil behavior, state and liquefaction sensitivity.

3.3. State parameter method

The behavior of the sand are influenced by both on density and on the stress level applied to the specimen. Based on critical state soil mechanics, the state parameter ψ, an important concept, is developed by Been and Jefferies [12]. The state parameter is determined by the void ratio difference between the current void ratio and the critical state void ratio at the same stress level, and combines the influence of void ratio and stress level into one defined parameter (Fig. 2). Saturated cohesionless soils their initial state lies above the critical state line (ψ>0) will show contractive volumetric response when subject to drained shear or experience strain softening and static liquefaction behaviour during undrained shear. To this end, the state parameter value can be used as an indicator of the state (stress level and density) and resistance of the soil.

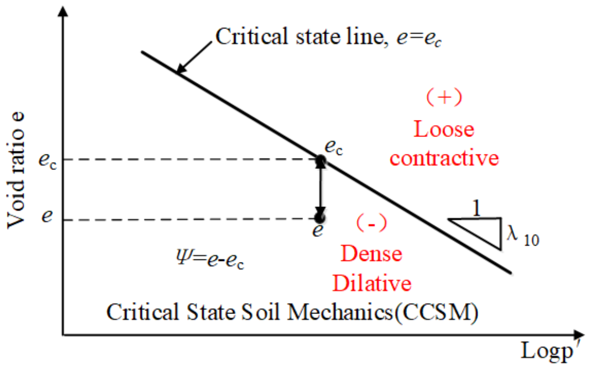


Figure 2. Definition of state parameter

The state parameter ψ presented in Fig. 2 can be obtained from CPTu data. Methods to obtain ψ from the CPT were first proposed by Been et al. [13-14], based on a body of calibration chamber data. Been et al. [15] suggested an extension that includes undrained and partially drained conditions by the normalized parameter B_q:

$$\psi = -\ln\left[Q_p\left(1-B_q\right)/\bar{k}\right]/\bar{m} \tag{3}$$

where Q_p =is a form of normalized cone resistance based on mean stresses, expressed as

$$Q_p = (q_t - p_0)/p_0' \tag{4}$$

where p_0 is the mean total stress and p'_0 is mean effective stress.

$\bar{k}$ and $\bar{m}$ continue primarily as functions of compressibility, defined as follows:

$$\bar{k} = \left(\frac{3+0.85}{\lambda_{10}}\right)M \tag{5}$$

$$\bar{m} = 11.9 - 13.3\lambda_{10} \tag{6}$$

M is critical state friction ratio, usually=1.2 in the absence of additional information. λ_{10} is the slope of the critical state line for all sands that can be calculated by the following two methods respectively [16-17].

$$\lambda_{10} = F_r/10 \tag{7}$$

$$\lambda_{10} = 1/(34-10I_c) \tag{8}$$

where I_c is the soil behavior index firstly proposed by Jefferies and Davies [18], and then revised to a form common usage by Been and Jefferies [17]. It is denoted in this study as $I_{c,BJ}$ to avoid confusion with the $I_{c,\ RW}$ proposed by Robertson [10].

4. Site description

The test site is located at a highway construction activity of highway in Suqian, Jiangsu Province, China. The test site lies in the alluvial plain of Quaternary-aged coastal plain deposits of abandoned Yellow River. Most of soil deposits in this region are composed of sand and silt. The peak horizontal ground surface acceleration (a_{max}), moment magnitude (M_w) of earthquake at this site are 0.15g and 8 degrees respectively. According to initial liquefaction screening of subsurface soil, the loose silty sand beneath the ground surface is highly susceptible to liquefaction.

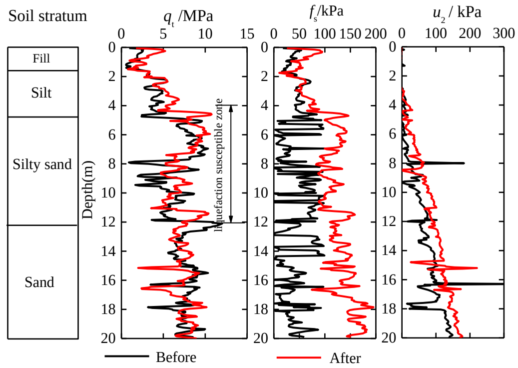


Figure 3. Soil layers and typical CPTu profiles of soils in the test site

Fig. 3 presents typical CPTu profiles including q_t, f_s, and u_2 before and after vibro-compaction. The q_t increased in most of the region as a result of compaction. The increase was large below the 1.8m, part of the compacted silt. It can be seen that the f_s also increased and the increment was almost constant throughout the soil layers compared with the q_t. Because of inadequate confinement, it is observed that q_t values of near surface soil (i.e.between 0-1.8m) only increase marginally. However, CPTu records after viro-compaction ground improvement exhibited higher values than before vibro-compaction in the liquefaction susceptible layers(4-12m). The results show that the compaction effect could be of great practical significance.

5. Results and analysis

5.1. Comparisons of parameters $(q_{c1N})_{cs}$ and Q_{tn}

Fig. 4 shows the representative Q_{tn} and $(q_{c1N})_{cs}$ profiles prior and following ground treatment. The comparison results indicated promising variations as a result of vibro-compaction in the liquefaction-susceptible layers. Fig. 4 shows that, for most of improved soil layers, the Q_{tn} and $(q_{c1N})_{cs}$ values were higher than 55 and 75 respectively. The soil state changed denser after ground improvement and reduced liquefaction hazard significantly. According to the criteria suggested by Campanella and Kokan [7], it was therefore that soil behavior changed from compression to dilation, the soil state changed from loose to dense. At the same time, as the boundary defined by Robertson [8], the loose sand changed to dense sand after vibro-compaction. It could be noted that $(q_{c1N})_{cs}$ gave more reasonable result compared to Q_{tn} and could be used as a more appropriate parameter for evaluation the vibro-compaction effect.

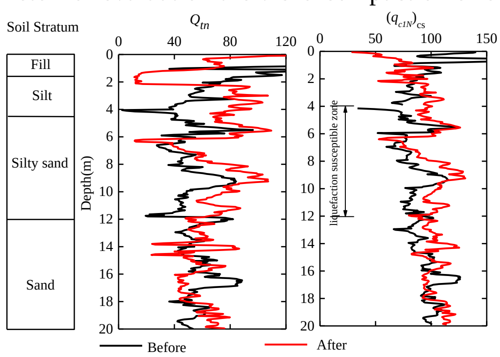


Figure 4. Evaluation of compactness based on Q_{tn} and $(q_{c1N})_{cs}$ criteria

5.2. Soil behavior classification charts

In fact, the soil behavior classification chart is based on the strength parameters of the soil indirectly measured from CPTu to behave like clay, silty clay, sand, silty sand, gravel, etc. After ground improvement, the soil types did not change and the strength parameters of the soil increased with increasing compactness and decreasing void ratio. Therefore, the evaluation of soil reinforcement effect can be carried out according to the soil behavior classification chart[11].

Fig.5 presents the records of some selected CPTu soundings plotted in the mentioned soil classification charts prior and following vibro-compaction ground improvement based on CPTu data. It clearly observed that some data is fall within the contractive region, the soils at some location or depths are not dense and have liquefaction potential. After treatment, most of the data is in the dilative region, indicting that the treated soils deposits are dense and the liquefaction risk decreases. More direct identification of liquefaction requires calculation of the factor of safety or the probability of liquefaction by combining field and laboratory tests. Additionally, it can be also observed that the the siginificance increase in sleeve friction or friction ratio and illustrates the increase in horizontal stress.

The results show that the Robertson method for soil behavior classification can give more intuitive sense and could be used as a more appropriate soil behavior classification charts for the effectiveness of the vibro-compaction ground improvement.

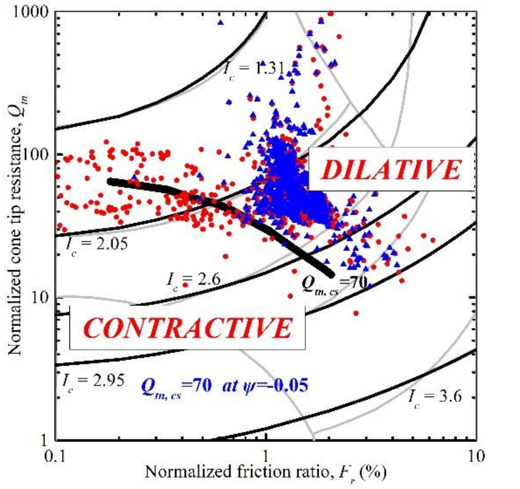


Figure 5. Soil behavior classification for Robertson (2009)

5.3. State parameter method

5.3.1. Comparison of $I_{c,RW}$ and $I_{c,BJ}$

In order to study state parameter, firstly, the soil behavior type indexes should be compared and interpreted. It should be noted that $I_{c,RW}$ proposed by Roberston and Wride neglected the pore pressure and was used in the NCEER method for liquefaction resistance for sandy soils[8]. They also suggested that the soil was likely not susceptible to cyclic liquefaction when $I_{c,RW}$ >2.6. While the inclusion of B_q in the formation of $I_{c,BJ}$ proposed by Been and Jefferies[17] was essential to allow to evaluate liquefaction resistance for a wider range of soils. What's more, the use of $I_{c,BJ}$ for developing the model of evaluating liquefaction resistance can remove the concern that the use of $I_{c,RW}$ as a proxy to the effect of " fines content " on liquefaction resistance. Both versions of I_c are compared in Fig. 6. It can be observed from the Fig.6 that the soil with $I_{c,RW}$<2.6 before vibro-compaction, indicting it has some liquefaction potential.

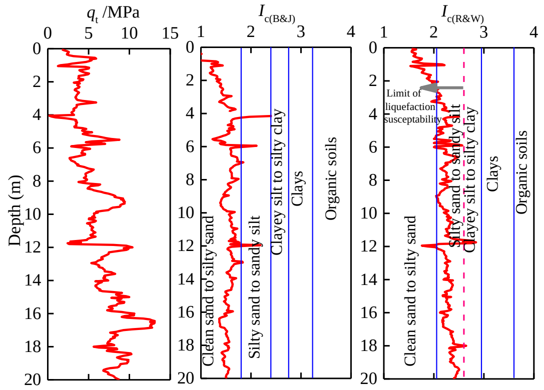
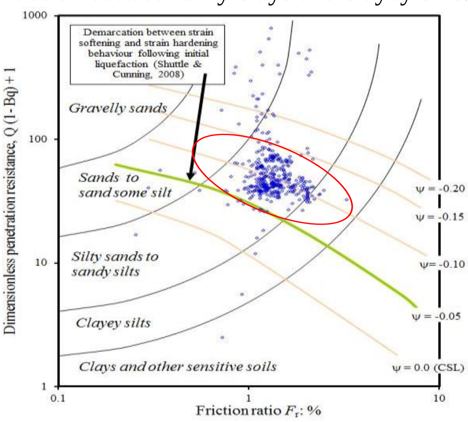


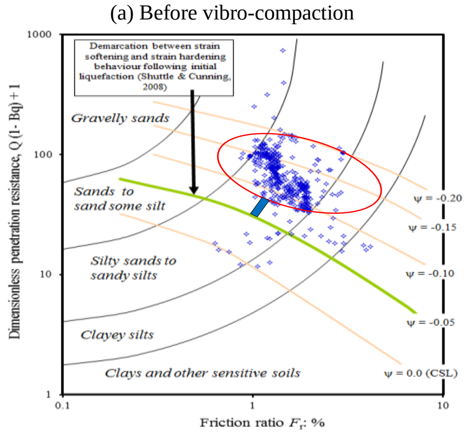
Figure 6. Comparison of soil classification index, $I_{c,BJ}$ and $I_{c,RW}$

5.3.2. Dimensionless classification chart

Figure 7 depicts the soil classification within the state parameter suggested by Jefferies and Been[19]. Consequently, according to the charts, most of the soils were in the silty sands to the sandy silts zone and ψ values were less than -0.05 zones. Jefferies and Been [19]had suggested that coarse-grained ideal soils with a state parameter ψ<0.05 will be dilative at large strains. In addition, the dimensionless term $\{Q(1-B_q)+1\}$ is "fundamental for the evaluation of undrained response during CPTU sounding". The term can allow for greater differentiation between silty clays and clayey silts.



(a) Before vibro-compaction



(b) After vibro-compaction

Figure 7. Dimensionless classification chart for soil behavior type on CPTu data

5.3.3. State parameter profiles

Relative density is extensively used expression to estimate the susceptibility for static liquefaction and in soil compaction project for quality control. The state parameter as an alternative approach to relative density can account for both sand density and effective stress as mentioned before. While the CPT data can be directly used to analyze liquefaction potential by Robertson and Wride method(i.e. the comparation of cyclic resistance ratio (CRR) and cyclic stress ratio (CSR))[20]. Fig.8 presents a representative profile about the variation of ψ and liquefaction potential based on CPTu data before and after vibro-compaction. It can be observed that the ψ values were more deviate from zero axis than the values in the liquefaction susceptible zone(4-12m) before vibro-compaction. This meant the state of soils changed to denser after vibro-compaction ground improvement, which is in good agreement with liquefaction potential analysis.

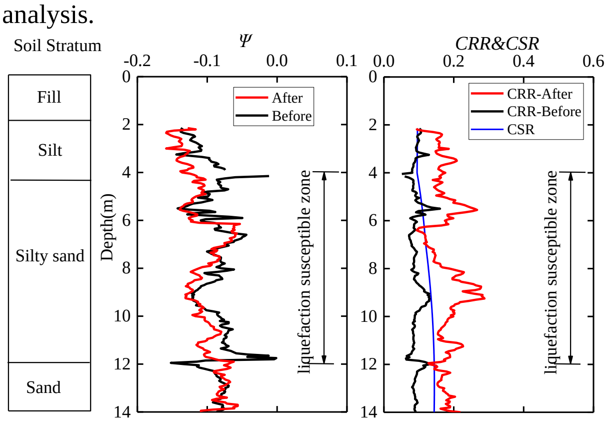


Figure 8. Analysis of state parameter and liquefaction potential

6. Conclusions

Based on the evaluation of vibro-compaction on soil liquefaction treatment through CPTu data, the conclusions can be drawn as follows:

(1) The investigated results indicated that vibro-compaction could change the soil state from loose (q_{c1N}<70) to dense (Q_{tn} >70) condition and soil behavior from contractive ($(q_{c1N})_{cs}$< 75) to dilative ($(q_{c1N})_{cs}$ >75) state. It is therefore derived that vibro-compaction can increase the compactness of soil and internal stability.

(2) The soil behavior classification charts based on CPTU data before and after vibro-compaction showed that the soils become denser and most of the soil deposits were out of the contractive(loose) zones. It illustrates the effectiveness of vibro-compaction for improving the liquefied ground.

(3) The state parameter can represent the current state of the soil and can be as a promising method for the evaluation liquefaction. The state parameter values were more away from zero than the values before vibro-compaction and the liquefaction potential of silty sand is also diminished in the liquefaction susceptible zone(4-12m) . It could pronounce that the state of soils changed to denser after vibro-compaction ground improvement.

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