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Non-plastic silty sand liquefaction, screening, and remediation

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ABSTRACT

Assessing liquefaction potential, in situ screening using cone penetration resistance, and liquefaction-remediation of non-plastic silty soils are difficult problems. Presence of silt particles among the sand grains in silty soils alter the moduli, shear strength, and flow characteristics of silty soils compared to clean host sand at the same global void ratio. Cyclic resistance (CRR) and normalized cone penetration resistance (q_{c1N}) are each affected by silt content in a different way. Therefore, a unique correlation between cyclic resistance and cone resistance is not possible for sands and silty sands. Likewise, the response of silty soils subjected to traditional deep dynamic compaction (DC) and vibro-stone column (SC) densification techniques is influenced by the presence of silt particles, compared to the response in sand. Silty soils require drainage-modifications to make them amenable for dynamic densification techniques. The first part of this paper addresses the effects of silt content on cyclic resistance CRR, hydraulic conductivity k, and coefficient of consolidation C_v of silty soils compared to clean sand. The second part of the paper assesses the effectiveness of equivalent intergranular void ratio $(e_c)_{eq}$ concept to approximately account for the effects of silt content on CRR. The third part of the paper explores the combined effects of silt content (viz effects of $(e_c)_{eq}$, k, and C_v) on q_{c1N} using laboratory model cone tests and preliminary numerical simulation experiments. A possible inter-relationship between q_{c1N}, CRR, accommodating the different degrees of influence of $(e_c)_{eq}$, k, and C_v on q_{c1N} and CRR, is discussed. The fourth part of the paper focuses on the detrimental effects of silt content on the effectiveness of DC and SC techniques to densify silty soils for liquefaction-mitigation. Finally, the effectiveness of supplemental wick drains to aid drainage and facilitate densification and liquefaction mitigation of silty sands using DC and SC techniques is discussed.

1. Introduction

1.1. Soil liquefaction and screening

Current liquefaction screening techniques rely on knowledge from extensive laboratory research conducted on liquefaction resistance of clean sands and field performance data during past earthquakes. Field observations have been documented in the form of normalized penetration resistance (SPT $(N_1)_{60}$, CPT q_{c1N}) [34,54,32,15], and shear wave velocity (v_{s1}) [2] versus cyclic stress ratio (CSR=τ/σ'_{vo}) induced by the earthquakes, corrected for magnitude, for many sites. Cyclic resistance ratio (CRR), applicable for a standard earthquake magnitude of 7.5, of a soil deposit with a known value of q_{c1N} is obtained from a demarcation line drawn between the field-observation-based data points which correspond to liquefied sites and those that did not liquefy as shown in Fig. 1. The CRR determined in this manner depends on fines content of the soil for a given q_{c1N}.

This has sparked numerous research on the effects of fines on cyclic liquefaction resistance of silty sands (e.g. [6,20,52,19,55,27]). Results show that silt content affects liquefaction resistance of silty soils compared to sand at the same void ratio. Studies also show that silt content also significantly affects permeability, compressibility, and consolidation characteristics of silty sands compared to sand [40]. The latter characteristics could influence cone penetration resistance as well. Two soils with the same stress-strain characteristics and liquefaction resistance but with different silt contents may have different permeability, compressibility, and coefficients of consolidation. Their cone resistance could be different due to different degrees of partial drainage, which may occur around the cone during penetration in each soil. A unique correlation between cyclic liquefaction resistance and penetration resistance may not be possible without considering the effects of fines, viz. coefficient of consolidation, on penetration resistance [43,44,48]. A correlation between cyclic resistance, cone resistance, compressibility and permeability characteristics may be possible.

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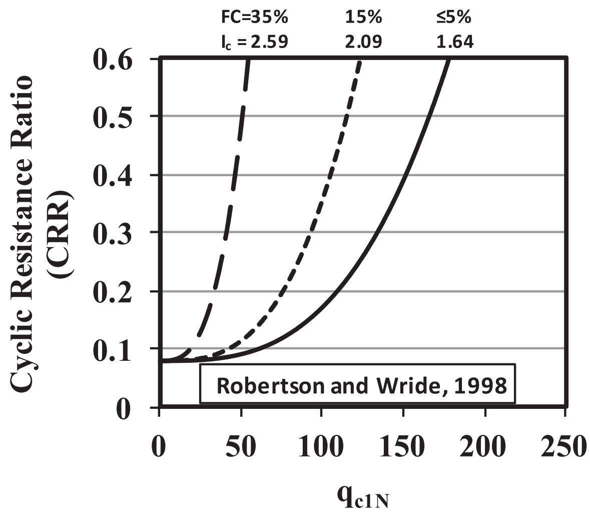

Fig. 1. Liquefaction screening charts – CPT.

1.2. Liquefaction mitigation by densification

Densification techniques such as dynamic compaction (DC) and vibro-stone column (SC) are among the most field proven and commonly used techniques for liquefaction mitigation in sands (Fig. 2a and c). The DC technique involves high-energy impacts to the ground surface by systematically dropping heavy weights of 5 to 35 Mg from heights ranging from 10 to 40 m to compact the underlying ground using heavy crawler cranes [22]. Vibro-stone column installation [11] process involves insertion of a vibratory probe with rotating eccentric mass and power rating in the vicinity of 120 kW. The probe plunges into the ground due to its self-weight and vibratory energy, which facilitates penetration of the probe. Once the specified depth (depth of stone column) is reached, the probe is withdrawn in steps (lifts) of about 1 m. During withdrawal of the probe, the hole is backfilled with gravel. During each lift the probe is then reinserted expanding the stone column diameter. This process is repeated several times until a limiting condition is achieved.

Densification of silty sand deposits containing high silt contents appears to be feasible only when these techniques are supplemented with wick drains (Fig. 2b and d) [13,21,8]. Traditionally, field design of these approaches rely on site specific field pilot trials and/or past experience based on case histories [22,3]. In the case of silty soils case histories are scarce. More recently advances have been made that enable detailed analyses of site response and changes in soil densities during DC and SC installations with due consideration for the influence of soil conditions including effects of silt content and soil permeability [23,36]. These advances allow a study of the effects of wick drains, spacing between wick drains, soil permeability, impact grid pattern and impact energy in the case of DC and diameter and spacing of stone columns in the case of SC on the degree of soil densification improvement achievable in the field, and select optimum field operation parameters for DC and SC for a site.

This paper presents a summary of (a) the recent advances on understanding of the influences of non-plastic fines on undrained cyclic resistance (CRR), permeability, coefficient of consolidation C_v, and cone penetration resistance q_{c1N} of silty soils, (b) possible relationships between CRR, q_{c1N}, and C_v, and (c) effectiveness of dynamic compaction and stone columns supplemented with pre-installed wick drains for liquefaction mitigation of silty sands. Simplified design charts for liquefaction mitigation using vibro-stone columns and dynamic compaction are also presented.

2. Effects of silt content on soil properties

2.1. Cyclic resistance (CRR)

Effect of non-plastic silt content on cyclic resistance has been the subject of research and much controversy in the early 80's until recently. A large data base [53] has been recently compiled based on available data in the literature on the effects of non-plastic fines content on undrained cyclic resistance of silty soils. The results indicate that the effect of non-plastic silt content on cyclic resistance can be appropriately accounted for using the equivalent intergranular void ratio concept [37,42,46,47]. This is illustrated below, using a few example data sets.

Fig. 3a shows the number of cycles (N_L) required to reach liquefaction versus void ratio for Ottawa sand/silt mix obtained from undrained cyclic triaxial tests conducted at a constant stress ratio (CSR) of 0.2 and initial confining stress of 100 kPa. The specimens were prepared by mixing Ottawa sand (D_{50}=0.25 mm) with a non-plastic silt (d_{50}=0.01 mm) at different silt contents (0 to 100% by weight). OS-15 in this figure refers to sand-silt mix at 15% silt content. At the same void ratio, liquefaction resistance of silty sand decreases with an increase in silt content. Beyond a transition silt content of about 20% to 30%, the trend reverses and liquefaction resistance increases with further increase in silt content. Similar observations have been widely reported in the literature (e.g. [52,55,19,27]).

The equivalent intergranular void ratio concept [37,42,44] proposes that mechanical properties such as liquefaction resistance of soils are dependent on the intergrain contact density of a soil, among other factors. Silty sand and sand at the same global void ratio are not expected to have the same intergrain contact density. Therefore, it is not appropriate to compare the liquefaction resistance of silty soil with that of clean sand using global void ratio as depicted in Fig. 3a. Sand-silt mixes and host sand are expected to show similar mechanical behavior if compared at a same contact density index. A soil classification system based on contact density was developed [42] and two contact density equivalent void-ratio indices, $(e_c)_{eq}$ and $(e_f)_{eq}$, respectively, were introduced for soils at silt content (FC) less than a threshold silt content FC_{th} and more than FC_{th}, respectively. $(e_c)_{eq}$ and $(e_f)_{eq}$ have been defined as

$$(e_c)_{eq} = [e + (1 - b)fc]/(1 - (1 - b)fc)] \quad (1a)$$

$$(e_f)_{eq} = [e/(fc + (1 - fc)/R_d^{\,m})] \quad (1b)$$

where fc=fines content by weight, R_d=ratio of the d_{50}'s of the host sand

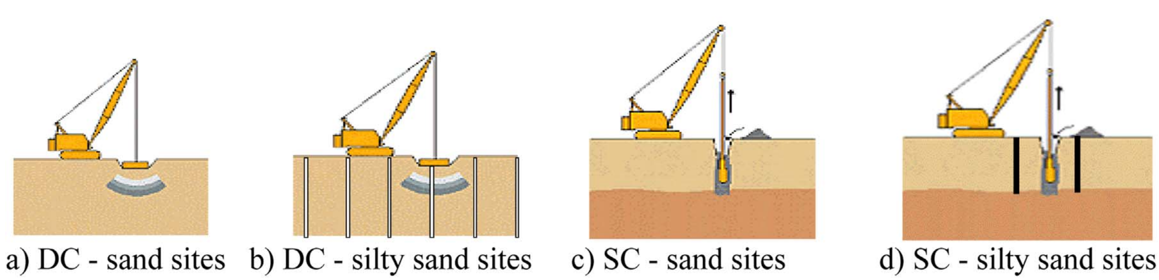

Fig. 2. Dynamic compaction and vibro-stone columns with and without wick drains.