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Influence of non-/low plastic fines on cone penetration and liquefaction resistance

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ABSTRACT

Uncertainties prevail at the current liquefaction screening method based on the cone penetration test (CPT) as to whether the existence of fines increases liquefaction resistance or decrease cone penetration resistance. In this study, field-based data are used to evaluate the effects of non-/low plastic fines on liquefaction resistance at the current CPT-based liquefaction assessment method. The first part of this paper examines the effects of the coefficient of consolidation or drainage characteristics of soils containing fines on cone penetration resistance. The coefficient of consolidation is influenced by the fines content and the relative density of the soil. The second part of this paper investigates the contribution of fines content less than 30% by weight on the liquefaction resistance of soils at different relative densities. Fines content over 30% by weight and/or high plasticity of fines can cause additional complications; therefore, it needs different valuation methods, which is beyond the scope of this paper. The liquefaction resistance of sands and silty sands is reinterpreted from the current CPT-based liquefaction assessment method. The trend, which presents the change of liquefaction resistance with fines content at the same relative density, is compared with the available laboratory-based data in the literature. The results show that the interpreted trend is not consistent with the laboratory-based correlations obtained by several previous researchers. Therefore, there will be probably some inaccuracies in estimation of liquefaction potential of silty sand using the current CPT-based liquefaction assessment method.

1. Introduction

Liquefaction is a devastating phenomenon by which loose saturated granular soils temporarily lose their shear strength during an earthquake as a result of the loss of particle contact and the development of excess pore pressures (Seed, 1976). Over the past four decades, since the liquefaction phenomenon was first explained, most research (Seed, 1976; Finn et al., 1971; Casagrande, 1975; Castro, 1975; Lee, 1976) has focused on clean sands (fines content less than 5%). However, as case study information has come to light, it is apparent that non-/low plastic silty sands and in some cases even silts, are frequently involved in liquefaction (Bray and Sancio, 2006; Idriss and Boulanger, 2008). As summarized in the state-of-practice paper by Youd et al. (2001), several in-situ tests are commonly used for the direct evaluation of the liquefaction potential of sandy soils, including the standard penetration test (SPT), cone penetration test (CPT or CPTu for piezocone penetration), and shear wave velocity test (V_s). The cone penetration test has gained worldwide attention because it can provide a continuous or near continuous profile, and it is rapid, repeatable, reliable, and cost effective when compared to the other field tests (Lunne et al., 1997; Mayne, 2007; Shuttle and Cunning, 2007). However, despite its appeal, the effect of fines content on the cone penetration resistance and cyclic resistance is not well understood. Also, the quantification of effects of fines on liquefaction resistance is difficult, and one encounters the problem of establishing a proper basis for comparison of sands containing fines and clean sand.

To facilitate the usage of the CPT in liquefaction analyses, numerous researchers have proposed relationships between liquefaction resistance and CPT measurements (Stark and Olson, 1995; Robertson and Wride, 1998; Juang et al., 1999; Carraro et al., 2003; Huang et al., 2005; Kokusho et al., 2005; Cai et al., 2012). Huang et al. (2005) performed a series of cone penetration chamber tests and cyclic triaxial tests on two different sand specimens with various fines contents and densities. The cyclic resistance ratio (CRR) was measured using stress-controlled cyclic triaxial tests when the soil specimens were consolidated under an isotropic effective confining stress of 100 kPa and 200 kPa. CRR was defined at a double axial strain of 5% in 15 cycles of uniform load application. The available data showed that the CRR-normalized cone penetration resistance (q_{c1N}) correlation developed from laboratory tests on two sand specimens consistently fell below the correlations proposed by Stark and Olson (1995). Kokusho et al. (2005) carried out miniature cone penetration tests and subsequent cyclic loading tests on the same triaxial test specimen. Mini-cone was penetrated into the specimen at a constant speed. The CRR was defined at a double axial strain of 5% in 20 cycles of uniform loading. The CRR-q_{c1N} relationship was established,

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and the available data showed that the points were concentrated in a narrow area, which may be represented by a single straight line. In fact, they found a single correlation between the CRR and the cone penetration resistance, despite large differences in relative density or fines content.

Based on the discussions in the 1996 NCEER and 1998 NCEER/NSF workshops (2001), the curve prepared by Robertson and Wride (1998) has accounted for the recently available data used in the final accepted liquefaction screening chart created from the field liquefaction observations and CPT tests (Fig. 1). This figure shows q_{c1N} versus cyclic stress ratio ($CSR = \tau_{ave}/\sigma_{vo}'$) induced by the earthquakes and corrected for 7.5 magnitude (M_w), at many sites where the liquefaction problem during earthquakes may or may not have been observed. The number of cycles (N) corresponding to 7.5 magnitude earthquake was suggested to be around a value of 15 (Finnie and Randolph, 1994; Green and Terri, 2005). This figure illustrates three CRR curves corresponding to the non-/low plastic fines content of $FC \leq 5\%$, $FC = 15\%$, and $FC = 35\%$. The clean sand based CRR curve ($FC \leq 5\%$) drawn between the liquefied, and the non-liquefied sites in the CPT-based liquefaction screening chart is adjusted by correcting the CPT tip resistance with the fines content correction factor (Robertson and Wride, 1998). The demarcation lines are used to determine the cyclic resistance ratio $(CRR)_{7.5}$, with a given value of q_{c1N}. In order to account for the differences in the number of cycles, frequency content etc., $(CRR)_{7.5}$ needs to be corrected by the magnitude scaling factor (Youd et al., 2001). This figure displays that the relationship between liquefaction resistance and cone penetration resistance is highly dependent on silt content. However, it is not clear whether the existence of fines increases liquefaction resistance or lowers cone penetration resistance.

In this study, field-based data are used (1) to gain detailed insight regarding the effects of non-/low plastic fines on normalized cone penetration resistance, and (2) to understand the effects of fines on liquefaction resistance at the current accepted CPT-based liquefaction assessment method proposed by Robertson and Wride (1998). Four in-situ tests (piezocone penetration test, pore pressure dissipation test, direct push permeability test, and standard penetration test) were conducted side by side at 20 different sites located on the northern coast of the Izmir Gulf in Turkey. The disturbed soil samples were retrieved from the SPT spoon for comprehensive laboratory testing. In the first part of this paper, field-and laboratory-test results, used to find the drainage effects of fines or consolidation characteristics of soils on cone penetration resistance at different relative densities are discussed. The second part focuses on the change of the liquefaction resistance of soils with relative density at different fines content. The liquefaction resistance of the soils is directly reinterpreted from the CPT-based liquefaction assessment method (Robertson and Wride, 1998). The interpreted trend of the CPT criteria does not provide consistent effects of non-plastic fines on liquefaction resistance with available laboratory-based correlations obtained by several previous researchers (e.g. Zlatovic and Ishihara, 1997; Polito and Martin, 2001; Chien et al., 2002; Thevanayagam and Martin, 2002; Kokusho, 2007; Cubrinovski et al., 2010).

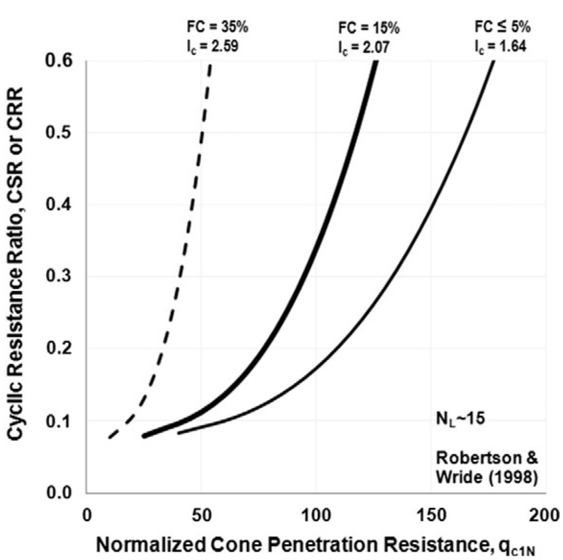

Fig. 1. CPT-based criteria for liquefaction resistance of clean sands and sands with fines (Robertson and Wride, 1998).

2. Field testing program

A set of four high-quality field tests were performed at 20 different locations on the Northern coast of the Izmir Gulf: (1) piezocone penetration test (CPTu), (2) pore pressure dissipation test (PPDT), (3) direct push permeability test (DPPT), and (4) standard penetration test (SPT). Fig. 2 displays a view of these test locations. As shown in Fig. 3a the set of tests listed above were conducted in proximity at each location, to minimize the differences in stratigraphy. This close spacing between the tests had the potential to influence the test results, were there to be any interference from previous soundings. For instance, the mud-rotary method used for drilling the SPT borehole could have affected the other three test results. In order to eliminate this effect, the sequence of the field tests was determined to be CPTu, PPDT, DPPT, and SPT.

The total sounding depth for each test was about 15 m. The test locations were carefully selected from the knowledge of the local geology preserved in the RADIUS project report (1999) and by considering the following criteria: (1) sandy soils must mostly contain 0–30% non-/low plastic fines content, given that fines content over 30% by weight and/or high plasticity of fines is known to affect liquefaction resistance of fines containing sands. (2) The groundwater level should be high enough to ensure that the data would be obtained under fully saturated conditions. In the study area, the soil consisted of mainly quaternary sediments. Quaternary unit consists of slope wash and alluvial soils, which are alluvial fan deposits with deltaic features. These sediments are mainly saturated and are formed by sedimentation of the alluvial deposits transported by the Gediz River. The above given tests and test area offered a test bed opportunity to examine the influence of fines on the cone penetration resistance and liquefaction resistance of soils. The field- and laboratory-test data were reported and analyzed at recent research projects TUBITAK-110M602 (2013) and EU-Marie Curie IRG-248218 (2014).

2.1. Piezocone penetration test — cone penetration resistance and pore pressure

The piezocone penetration testing (CPTu) device used in this study was manufactured by Geotech Inc., Sweden. These tests were conducted by using the Geotech CPT classic probe, which has 60° tip angle and 35.7 mm diameter (10 cm^2 tip area). As shown in Fig. 3b, the independent measured parameters are cone penetration resistance q_c, friction resistance f_s, and pore water pressures above the cone face (referred to as the u_2 position) for each 1 cm of penetration. The measured data were digitized inside the probe and then transferred acoustically (without a cable down the hole) to the data acquisition system on the ground surface. This procedure was faster than using cables and provided a continuous profile for all test results. In order to obtain a satisfactory pore pressure response during a piezocone test, complete saturation of the piezocone was essential. Hence, before starting each CPTu sounding, the porous element was saturated with glycerin (Campanella et al., 1986). At each location, CPTu soundings were performed with a constant penetration speed of 20 mm/s (ASTM D3441). The measured cone penetration resistance and friction resistance values were normalized based on the equations stated below (Youd et al., 2001):

$$q_{c1N} = C_q \left(\frac{q_c}{P_a}\right) \tag{1}$$