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REVIEW ARTICLE

The effects of small particles on soil seismic liquefaction resistance: current findings and future challenges

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Abstract The natural and artificial sand soils always incorporate other small particles, which makes the soil liquefaction resistance difficult to predict. The particle size may change from 10^{-5} m (e.g., fine particles) to 10^{-8} m (e.g., ultrafine particles), and the soil behaviors change dramatically when such particles are present. Newly reported soil liquefaction cases involving fine particles provide great challenges to seismic design codes. To make it clear, this paper reviewed effects of small particles on soil liquefaction in three different types. The non-low plastic fines (5–75 μm), clay particles (0.1–5 μm), and ultrafine particles (1–100 nm) are discussed, respectively. Many scholars found that liquefaction resistance decreased at first but increased as fine particles (non-low plastic fines or clay particles) were added. This phenomenon can be attributed to the lubrication effect of fine particles. However, when particles in nanometer scale, the strong bond between particles and hydration adsorption of nano-suspension improve liquefaction resistance. There are still many challenges to understanding the roles of small particles in liquefaction, for example, determining relative density for a high fine content, determining particle shape effect (e.g., aspect ratio, flatness, and particle roundness), as well as the long-term reinforcement performance of ultrafine particles. In engineering practice, it suggests that the seismic design codes address the effects of non-plastic fines in laboratory tests. As for some new liquefaction mitigation methods by ultrafine particles, we believe that the standard penetration test may not be appropriate to evaluate soil improvement effect, because the test results cannot reflect the properties change of pore water.

Keywords Liquefaction resistance · Fine particles · Clay particles · Ultrafine particles · Seismic design

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1 Introduction

Since the Niigata and Alaska earthquakes in 1964, many researches have been carried out on soil liquefaction. Soil seismic liquefaction occurs due to the increase in excess pore water pressure of soil. It will cause huge disasters to human populations (Juang and Li 2007; Huang and Jiang 2010; Bhattacharya et al. 2011; Huang and Yu 2013). In studies of soil liquefaction, fine and ultrafine particles play an important role, because these small particles influence soil instability (Abedi and Yasrobi 2010), static shear strength (Yang and Wei 2012), and cyclic shear strength (Beroya et al. 2009). The size of small particles is about nano- and microscale (Otterstedt and Brandreth 1998), and it incorporates three different types of particles (from 1 nm to 75 μm) based on the review of this problem. In particular, the non-low plastic fines, clay particles, and ultrafine particles were considered as distinct categories because of their very different size and properties. The specific definition of particles size will be introduced in Sect. 2.

The effects of fine particles on soil liquefaction have been known since the 1970s. A Chinese liquefaction susceptibility criterion was first proposed by Wang (1979). This famous criterion considers the effects of fine particles based on the observed failures following the 1975 Haicheng and 1976 Tangshan earthquakes. Seed and Idriss (1982) modified this "Chinese criterion," pointing out that soil types and clay content (Cc) are crucial to liquefaction, since soils with clay fines (< 5 μm) of more than 15% will not be liquefied. Seed et al. (1985) also found that fine particles (< 75 μm) influence standard penetration test (SPT) blow counts (Fig. 1), with liquefaction resistance increasing with increasing fine content (Fc). Tokinatsu and Yoshimi (1983) came to the same conclusion for soils containing clay particles.

Although it believes that the soils with high Fc or Cc will not liquefy, there are many cases of soils with high Cc that were reported to have liquefied during strong earthquakes (Tan et al. 2013). For example, soils containing 19% Cc were found to be liquefied in the Chi-Chi earthquake (Hwang and Yang 2001), as well as the Marmara (Turkey) earthquake (Bol et al. 2010). This has led to ongoing discussion of the roles of small particles in liquefaction. More recently, scholars have found that ultrafine particles (e.g., nano-

Fig. 1 Relationship between cyclic stress ratio (CSR) and standard penetration tests (SPT blow count $(N_1)_{60}$; after Seed et al. 1985). Note: Fc = fine content
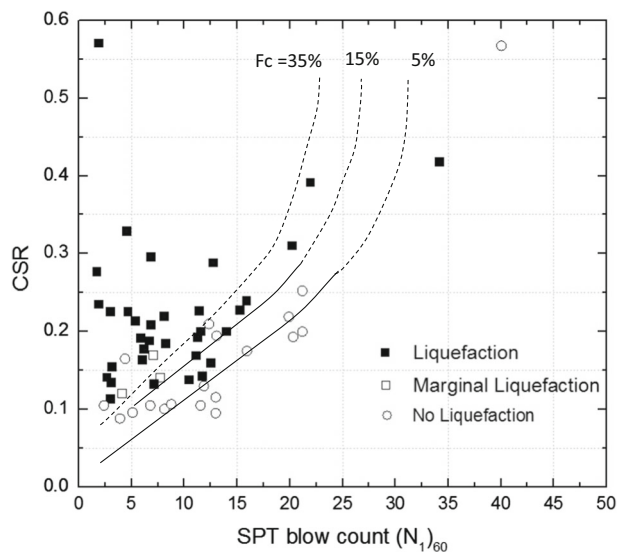
bentonite) inhibit the generation of pore water pressure, and those particles can be used to mitigate soil liquefaction (Gratchev et al. 2007; El Mohtar et al. 2008, 2013). In addition, there are many indices used to evaluate soil liquefaction resistance for soils containing clay particles, including Cc (Ghahremani and Ghalandarzadeh 2006), plasticity index (PI) (Boulanger and Idriss 2006), as well as the content of specific clay minerals (Beroya et al. 2009).

In this paper, the effects of small particles on the liquefaction resistance were reviewed based on three different particles. In addition, we outline the research challenges related to working on soil liquefaction of soils containing small particles.

2 The effects and mechanisms of small particles on soil liquefaction

To begin with, the size of small particles should be discussed. The definitions are similar in different codes (Ministry of Water Resources of China 2007; American Society for Testing and Materials 2011; Chen et al. 2012), with fine particles being < 75 µm in size. Most scholars also use 75 µm as the critical size value (Graham and Elton 2011), and the Chinese code (Ministry of Water Resources of China 2007) further defines fine particles into silt (5–75 µm) and clay (< 5 µm) (Fig. 2). In the fields of nanoscience and nanotechnology, ultrafine particles, also called nanoparticles (U.S. EPA 2004; Oberdörster
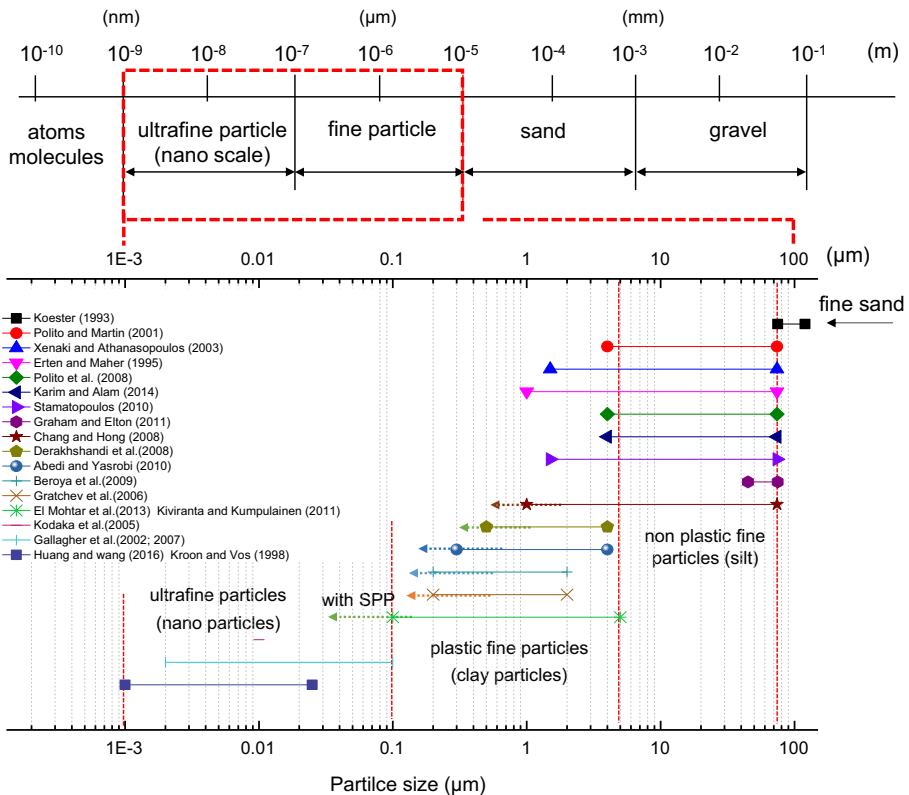

Fig. 2 Particle size ranges for small particles in various studies. Note: SPP = sodium pyrophosphate

et al. 2005), have at least one dimension measuring from 1 to 100 nm (National Science and Technology Council 2007). To illustrate the variability in definitions, size ranges used in recent researches on small particles are shown in Fig. 2. In short, soil particles less than 75 μm are further classified as: (1) non-plastic fines (5–75 μm), although some scholars also use the term non-low plastic fines or pure silt for this range; (2) plastic fines (0.1–5 μm), although plastic fines are in fact clay particles (Ghahremani and Ghalandarzadeh 2006; Abedi and Yasrobi 2010); and (3) ultrafine particles. In most studies, the lower limit size for clay particles is not clearly defined (Fig. 2); hence, we have given it as a dashed arrow. Here, we take 0.1 μm as the lower limit of clay particle size (El Howayek et al. 2014; Huang and Wang 2016a). We also equate clay particles with plastic fines. It is clear that some scholars (Gratchev et al. 2006a, b) have used different definitions for fine and clay particles, for example, < 63 and < 2 μm, respectively. However, we believe that the effects and mechanisms of liquefaction for these types of particles are more relevant than defining a very specific value for their ranges.

Given the diversity of soil particles (Fig. 2), below we consider non-low plastic fine particles, clay particles, and ultrafine particles as distinct categories because of their very different size.

2.1 Documented effects of small particles on soil liquefaction

2.1.1 Non-low plastic fine particles

Based on the researches of non-low plastic fines, the results clearly show a turning point in liquefaction resistance, as non-low plastic fine particles are added to soils.

Using non-low plastic fines, Troncoso (1990) did tests with silt contents of 0–30% ($e = 0.85$); these tests showed that liquefaction resistance decreased, but then increased, as Fc increased (Fig. 3). Koester (1993) also studied the influence of Fc on liquefaction resistance, the cyclic resistance ratio (CRR) decreased at first, but then increased, as Fc exceeded 20%. Clearly, both studies show similar patterns of liquefaction resistance. Polito and Martin (2001) carried out stress-controlled cyclic triaxial tests on liquefiable sand, with Fc of 0–100% ($e = 0.68$). Figure 3 shows that cyclic resistance decreases dramatically, when fine particles are added, with Fc of 35% corresponding to the minimum value of
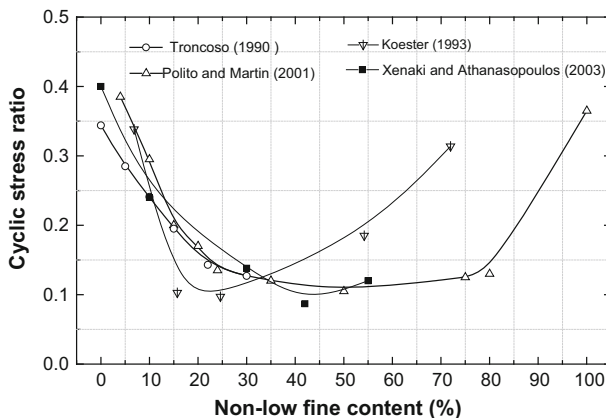

Fig. 3 Relationship between non-low plastic fine content and liquefaction resistance in various studies

cyclic resistance. Similar results were obtained by other scholars (Xenaki and Athanasopoulos 2003; Polito et al. 2008; Karim and Alam 2014). The microcosmic model by Thevanayagam (1998, 2000) can be used to investigate the roles of non-low plastic fine particles (Polito and Martin 2001; Chang and Hong 2008). In Fig. 4, the transitional fine content (TFC) is 38% for particles having the same specific gravity (if $e_1 = 0.7$, and $e_2 = 0.9$). This is very close to values for the lowest liquefaction resistance observed in laboratory studies (Xenaki and Athanasopoulos 2003).

2.1.2 Clay particles

A decrease in liquefaction resistance followed by an increase also occurs when clay particles are added to sand (Fig. 5). Typically, the Cc is less than 20%, when this increase occurs, and the sand grains are not yet separated, which is different from non-low plastic fines.

Georgiannou et al. (1990) tested kaolin–sand mixtures and pointed the clay particles reduce the contact forces between sand particles. Heng et al. (2001) studied the effects of specific clay minerals, kaolinite and illite (Fig. 5). They found that the minimum liquefaction resistance occurred at a Cc of about 9%. The effect that clay particles (kaolinite) reduce liquefaction resistance also has been verified by other scholars (Ghahremani and Ghalandarzadeh 2006; Chang and Hong 2008; Derakhshandi et al. 2008), with a Cc of 9–12%, corresponding to the lowest liquefaction resistance of these soil mixtures (Fig. 5). The higher specific surface area of montmorillonite makes it shows more intense hydration than kaolin (Beroya et al. 2009), which makes it a little different. Bentonite containing montmorillonite shows little lubrication effect on liquefaction resistance (Kiviranta and Kumpulainen 2011; El Mohtar et al. 2013). Gratchev et al. (2006a, b) found that with increasing content of bentonite particles, the number of cycles required to reach liquefaction decreased gradually, with contents of 7–8% corresponding to the lowest liquefaction resistance (Fig. 5).

2.1.3 Ultrafine particles

Ultrafine particles always related to medicine, environment, and food engineering (Valencia et al. 2015). Now they are hot topics because those particles can be used to mitigate soil liquefaction.

Fig. 4 Microcosmic mechanism model for various arrangements of fine and coarse particles (based on concepts of Thevanayagam 2000; Xenaki and Athanasopoulos 2003; Chang and Hong 2008). Note: e_1 and e_2 are overall void ratio of pure sand and fine particles, respectively
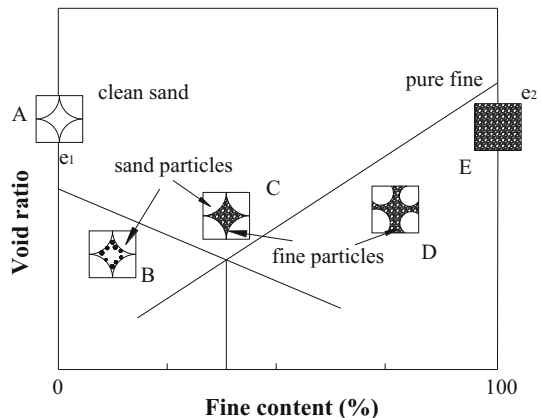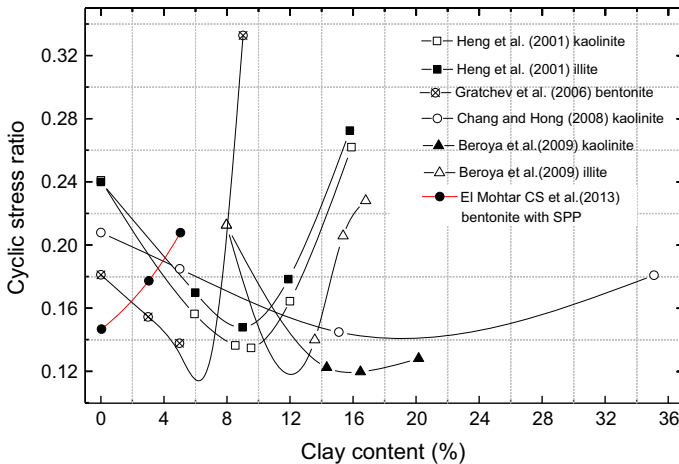
Fig. 5 Relationship between clay content and liquefaction resistance ($N = 10$) in various studies. Note: The red line shows the increasing effect of bentonite with sodium pyrophosphate

Among such particles, there are different particle shapes: spherical and sheet shaped. Colloidal silica has a spherical shape, with particles of 7–22 nm in size. Chang et al. (1994) pointed out that colloidal silica has excellent durability, even at 5% concentration (Gallagher and Mitchell 2002; Gallagher et al. 2007a, b). Kodaka et al. (2005) observed that cyclic shear strength improved markedly in soils treated with colloidal silica. Likewise, addition of ultrafine particles with sheet structures resulted in a liquefaction resistance increases of soil composites. It has been found that 10% nano-bentonite suspensions form a gel, which improves the liquefaction resistance of soils (El Mohtar et al. 2008). In addition, in Fig. 5, sodium pyrophosphate can be used to modify the behaviors of these bentonite suspensions (Rugg et al. 2011; El Mohtar et al. 2013). Like bentonite and natural montmorillonite, laponite is a silicate nanoparticle with a layered structure having a particle thickness of about 1 nm and a diameter of about 25 nm (Kroon et al. 1998). It performs even better than nano-bentonite in mitigation of soil liquefaction (El Mohtar et al. 2008). Huang and Wang (2016a) found that the liquefaction resistance increased 30–80% at very low laponite concentrations (wt. 2.5–3.5%).

2.2 The mechanisms of small particles on soil liquefaction

In Sect. 2.1, we described effects of small particles on soil liquefaction resistance. The reduction in liquefaction resistance was observed for fine particles. However, soil liquefaction resistance increased when ultrafine particles were added. This phenomenon is attributed to interactions between particles linked to their size.

Certainly, there are marked changes in the soil particle size as shown in Fig. 2 and sizes for non-low plastic fines range between 75 and 5 μm, while ultrafine particles are less than 0.1 μm in size. From fine to ultrafine particles, the particle size changes rapidly, which makes the specific surface area increasing and mineral structures different (Wu et al. 2015). Thus, the mechanisms are very different due to the change in particle size. From fine to ultrafine particles, the effect of small particles changes from mechanical friction to hydration adsorption, and the clay particles may show both effects. In short, in micrometer

scale, fine particles mainly affect the interaction of sand particles; in nanometer scale, ultrafine particles mainly affect the pore fluid properties (Huang and Wang 2016a).

Besides the main mechanisms of particle size effect, a number of other sub-mechanisms of small particles also complicate this issue. Clearly, the lower hydraulic conductivity of fine particles may also appear to decrease the liquefaction resistance (Belkhatir et al. 2013). The clay particles will show a weak bonding effect between sand particles. In addition, some of the ultrafine particles show both effects of cement and pore fluid properties change (Huang and Wang 2016b).

3 The challenges of small particles on soil liquefaction

In the past decades, many researches have been carried out on effects of small particles on soil liquefaction; some mechanisms can be drawn, while there are still many challenges to be overcome including laboratory tests and seismic design in engineering.

3.1 Challenges of small particles for laboratory tests

The relative density and particle shape are the research challenges for non-low plastic fine particles in laboratory tests. Many scholars have studied the relative density of sand containing silt (Polito and Martin 2001; Nabeshima et al. 2002; Sadek and Saleh 2007; Stamatopoulos 2010). However, there is no procedure for determining maximum or minimum density for soils with Fc > 15% (American Society for Testing and Materials 2006a, b). Figure 6 shows the conflicting conclusions of scholars at different relative density (Singh 1996; Polito and Martin 2001; Sadek and Saleh 2007; Karim and Alam 2014). Most researches only focus on liquefaction resistance related to Fc, which is clearly insufficient. The shape of fine particles has a great influence on soil performance (Dai et al. 2015; Yang and Luo 2015). An angular-to-angular model produced the most stable structures and fines having a rounded shape caused a marked increase in liquefaction potential (Yang and Wei 2012; Wei and Yang 2014).
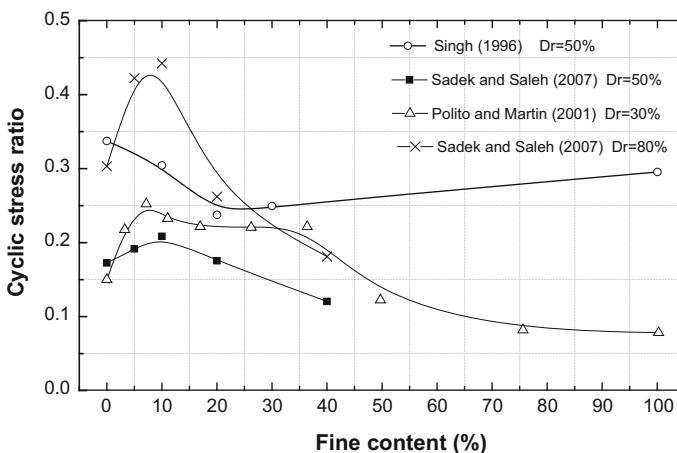

Fig. 6 Effect of fine content on liquefaction resistance (constant relative density) in various studies

The plastic index of clay particles on soil liquefaction still needs more research. PI has a great influence on soil properties; when PI > 7, the soils are clay like, while when PI < 7 are sand like (Boulanger and Idriss 2006). Tokinatsu and Yoshimi (1983) concluded soils still have potential to be liquefied if the PI is low. Guo and Prakash (1999) analyzed data from El Hosri et al. (1984) and concluded that with increasing plasticity, liquefaction resistance of soils decreased at first and then increased (Fig. 7a). Sadek and Saleh (2007) also found that as plasticity increased, liquefaction resistance decreased (Fig. 7a). In Fig. 7b, the increasing PI increases the liquefaction resistance when PI > 10 (Ghahremani and Ghalandarzadeh 2006; Gratchev et al. 2006a). Thus, some scholars have discussed whether PI can be used to evaluate liquefaction resistance (Gratchev et al. 2006a; Beroya et al. 2009); however, there seems no consistent conclusion.

The micro-reinforcement mechanism and long-term reinforcement performance of ultrafine particles still pose enormous challenges for researchers. The particle shapes of ultrafine particles are different, which makes the micro-reinforcement mechanisms diverse. However, the current researches pay more attention to the reinforcement effects on ultrafine particles (Huang and Wang 2016b). Moreover, the ultrafine particles are very sensitive to environment changes, which brings challenges to long-term reinforcement performance of those particles. For example, the properties of colloidal silica change dramatically with changes in pH (Gallagher and Mitchell 2002; Gallagher et al. 2007a, b). Likewise, nano-bentonite undergoes properties change with addition of sodium pyrophosphate (Rugg et al. 2011; El Mohtar et al. 2013), and it is very sensitive to temperature (Turan et al. 2009). Laponite suspensions show high sensitivity to both pH and ionic concentration (El Howayek et al. 2014). In addition, the safe use and toxicity of ultrafine particles also require further research (Service 2003; Gilbert 2009; Dejong et al. 2010).

Obviously, there are still many research challenges to understanding the roles of those particles on soil liquefaction for laboratory tests. In addition, more tests are required to compare the liquefaction resistance of soils containing those small particles.

3.2 Challenges of small particles for seismic design in engineering

For initial assessment of the liquefaction potential of soils in engineering projects, the current seismic design codes are clearly not appropriate. For example, the modified
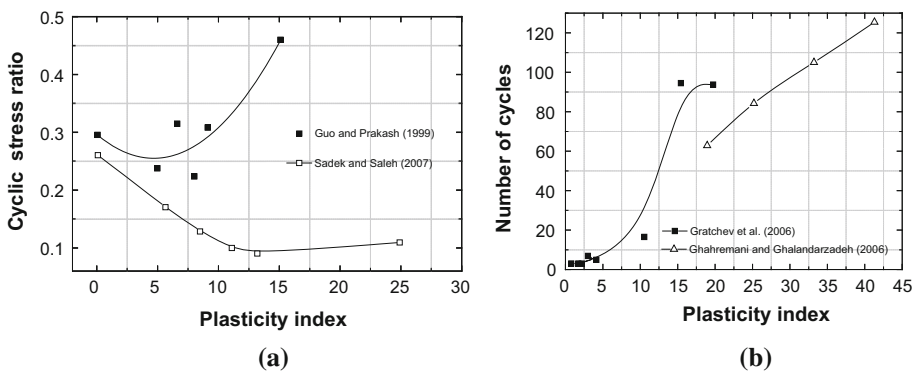

Fig. 7 Effect of the plasticity index on soil liquefaction resistance in various studies during **a** cyclic resistance; and **b** over a number of cycles

"Chinese criterion" by Seed and Idriss (1982), the recommended criteria by Andrews and Martin (2000), and the "code for seismic design of buildings" (Ministry of Construction of China 2010), all point when Cc more than 10–16%, the soils will not be liquefied. However, investigations of both Chi-Chi (Hwang and Yang 2001) and Marmara (Bol et al. 2010) earthquakes found that soils containing 19% Cc were liquefied.

For in situ assessment of liquefaction resistance in engineering, the standard penetration test, cone penetration test, and shear wave velocity test are used for evaluation of soils containing fine particles. The SPT is widely applied in engineering practices, and many scholars have discussed this method (Youd et al. 2001; Hwang and Yang 2001; Cetin et al. 2004; Bol et al. 2010; Boulanger and Idriss 2012). There are many procedures considering the effects of fine particles, e.g., the procedure proposed by the National Center for Earthquake Engineering Research (NCEER) (Youd et al. 2001), the Japanese seismic design code for roads and bridges (Japan Road Association 2002), and the Chinese seismic design code for buildings (Ministry of Construction of China 2010). Although those procedures based on SPT consider the influence of Fc or Cc by correction coefficients, the correction coefficients are different from each other. More details (related formulas) can be obtained in the references (Youd et al. 2001; Japan Road Association 2002; Ministry of Construction of China 2010). In addition, the in situ tests may consider little about lubrication effects at low Fc that got by laboratory tests. Moreover, some scholars pointed the Cc does not take the effects of fine particles into account, and only Fc used in codes is insufficient (Seed et al. 2003; Bray and Sancio 2006; Cubrinovski et al. 2009). Thus, we suggest that the SPT criteria should also address the effects of fine particles in laboratory tests.

Ongoing laboratory researches have highlighted some effects of ultrafine particles on liquefaction that need to be addressed in engineering, especially in the assessment of liquefaction resistance using in situ tests. Many new liquefaction mitigation methods have been introduced into engineering practices (Huang and Wen 2015). Among those methods, the ultrafine particles can inhibit the generation of pore water pressure and have been researched to mitigate soil liquefaction (Gallagher and Mitchell 2002; Gallagher et al. 2007a, b; Gratchev et al. 2007; El Mohtar et al. 2008, 2013; Huang and Wang 2016a). Some newly ultrafine methods focus on inhibit the generation of pore water pressure; however, the SPT may not be appropriate to evaluate soil improvement effect, because the N counts only represent the soil mechanical strength not including the properties change of pore water.

4 Conclusions

This paper reviewed the recent studies of small particles on soil liquefaction resistance, and several conclusions can be drawn:

1. The particle size changes associated with adding non-low plastic fine particles to ultrafine particles, and these particles have a huge influence on soil behaviors. The existence of non-low plastic fine particles will decrease liquefaction resistance. In fact, the smaller the fine particles, the lower of Fc that corresponds to the minimal liquefaction resistance. However, for ultrafine particles, the liquefaction resistance will increase, even at very low content. Clay particles show both effects, depending upon on the Cc and clay mineralogy.

2. From fine to ultrafine particles, the effect of small particles changes from mechanical friction to hydration adsorption, which makes the mechanisms very different from each other. In short, in micrometer scale, fine particles mainly affect the interaction of sand particles while in nanometer scale, ultrafine particles mainly affect the pore fluid properties.

3. There are still a number of research challenges for small particles. Clearly, relative density may not be a suitable parameter for high Fc soils, because there is no test method to determine relative density at high Fc. In addition, fine particles shape, the effects of plasticity of the clay particles, and the long-term reinforcement performance of ultrafine particles require further attention.

4. The effects of fine clay particles on the seismic design codes and laboratory tests are inconsistent. In addition, the SPT may not be appropriate to evaluate soil improvement effect of ultrafine particles, because the tested counts cannot incorporate the properties change of pore water.

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