AN OVERVIEW OF LIQUEFACTION SUSCEPTIBILITY CRITERIA

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ABSTRACT: Ground failure case histories after 1994 Northridge, 1999 Chi-Chi and 1999 Kocaeli earthquakes showed that the mixture of low-plasticity silt-clay generate significant cyclic pore water pressures and can exhibit a strain softening response, which may cause damage to overlying structural systems significantly. These observations accelerated the research studies on liquefaction susceptibility of fine-grained soils. Chinese Criteria proposed by Wang (1979) was the first notable effort to identify the potentially liquefiable fine-grained soils. These criteria have been used with some modifications (e.g. Seed et al.1983, Finn 1993) until the case histories compiled after some recent earthquakes (e.g. 1994 Northridge,1999 Kocaeli, 1999 Chi-Chi) verified that their original form as well as their modifications cannot successfully identify the soils liquefied during and after these earthquakes. This fact has accelerated the studies focusing on development of new criteria. Based on the field observations and laboratory cyclic tests results on "undisturbed" samples from liquefied sites, Seed et al. (2003), Bray and Sancio (2006) and Boulanger and Idriss (2006) have proposed the new criteria of fine-grained soils for the assessment of liquefaction potential. Alternative approaches to Chinese Criteria were proposed by several researchers (Seed et al. 2003, Bray and Sancio 2006, Boulanger and Idriss 2006) most of which assess liquefaction triggering potential based on cyclic test results compared on the basis of index properties of soils (such as LL, PI, LI, wc/LL). Although these new methodologies are judged to be major improvements over Chinese Criteria, still there exist unclear issues regarding if and how reliably these methods can be used for the assessment of liquefaction triggering potential of fine grained soils.

Keywords: Liquefaction Susceptibility, CPT, Fine-grained Soils, Cyclic Tests.

1. INTRODUCTION

During earthquakes, soil liquefaction has been one of the major causes for damage and loss lot of lives. The phenomenon in which, significant loss in shear strength and stiffness occur due to increase in pore water pressure known as liquefaction. After devastating damages due to liquefaction observed during and after 1964 Niigata Japan and Great Alaska earthquakes, several researches have been carried out to understand this phenomenon better. Almost five decades have passed after the pioneer studies, and the numbers of both case histories and high-quality test data has increased. Yet, there are still some unknowns waiting to be resolved. Until Haicheng (1975) and Tangshan (1976) earthquakes, it was believed that only "clean sandy soils" with few amount of fines do liquefy and cohesive soils were considered to be resistant to cyclic loading due to cohesional component of shear strength. However, those earthquakes showed that even cohesive soils could liquefy (Wang, 1979, 1981, 1984). 1994 Northridge, 1999 Adapazari and 1999 Chi-Chi earthquakes further illustrated that silty and clayey soils may exhibit soil liquefaction response. In compliance with these observations, liquefaction susceptibility criteria for fine grained soils were improved by various researchers (e.g. Chinese Criteria 1979, Seed et al. 1983, Finn et al. 1994, Andrews and Martin 2000, Seed et al. 2003, Bray and Sancio 2006, Boulanger and Idriss 2006).

2. LIQUEFACTION SUSCEPTIBILITY CRITERIA

Several researches have focused on liquefaction susceptibility of fine grained soils. Major improvements were established by every new lesson gathered through every new earthquake. There is an overview of the journey of the evaluation of liquefaction susceptibility of fine grained soils starting with discussion of Chinese criteria, followed by Andrews and Martin (2000). Then, it continues with the recent criteria suggested by Seed et al. (2003), Bray and Sancio (2006) and Boulanger and Idriss (2004, 2006). Lastly, other criteria suggested by various researchers are summarized.

2.1 Chinese Criteria

Liquefaction susceptibility criteria proposed by Wang (1979), known as Chinese criteria, is based on the failures observed due to liquefaction in fine-grained soil profiles after 1975 Haicheng and 1976 Tangshan earthquakes occurred in China. A database was compiled from sites where liquefaction was observed. This database was composed of cohesive soils, whose clay fraction is less than 20%, LL is between 21 to 35, PI is between 4 to 14 and wc/LL > 0.90 (Wang, 1979). According to Unified Soil Classification System, most of the fine grained soils were classified as low plasticity clays (CL) or silty clays (CL-ML). According to Chinese criteria, if clayey soils contain 15-20 % of particles by weight smaller than 0.005 mm and they have wc/LL ratio greater than 0.90 are susceptible to liquefaction. The modification of Chinese criteria by Seed and Idriss (1982) known as "Modified Chinese Criteria". It states that "clayey soils", soils lying above A-line, are vulnerable to liquefaction only if they satisfy all following these three conditions: (i) percentage of soil particles smaller than 0.005 mm should be less than 15%, (ii) LL should be less than 35 and (iii) wc/LL > 0.90 (Seed and Idriss, 1982). In 1992 Koester indicated that fall cone apparatus which is used in Chinese practice, determined LL values about 3% to 4% greater than the values obtained by standard Casagrande percussion device. Hence a reduction in Liquid limil criteria was proposed.

Main limitations of this criterion can be summarized as follows: (i) data used in these studies were obtained from only two earthquakes which produced only a limited range of peak ground acceleration or corollary CSR levels, (ii) Chinese liquid limit and percentage of fines definitions do not comply with widely used standard definitions. Hence, their use for i) earthquake excitations producing significantly different level or duration of shaking and ii) for sites which exhibit significant different characters than the regional fine grain soils is questionable.

Following case histories also supported the fact that Chinese Criteria cannot successfully identify the potentially liquefiable soils. After 1989 Loma Prieta earthquake, based on their observations, Boulanger et al. (1998) proposed that in Moss Landing Site the ground failure observed can be due to cohesive materials and also stated that without laboratory testing the use of Modified Chinese criteria should be avoided.

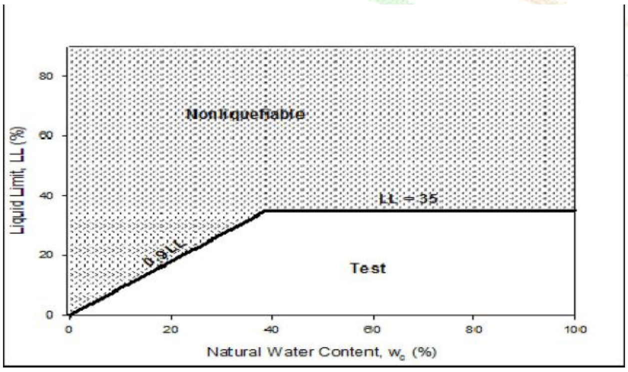

Fig.1: Modified Chinese criteria (Seed & Idriss, 1982)

Similarly, after Northridge earthquake (1994), Holzer et al. (1999) reported that the ground deformations at Malden Street Site were primarily due to liquefaction. According to Modified Chinese criteria that site was composed of "low strength lean clays" which were not considered to be susceptible to liquefaction. Holzer et al. stated that these observations were consistent with the findings after San Fernando earthquake1971.

Bray and Sancio, (2006) reported that during 1999 Chi-Chi and 1999 Adapazari earthquakes, according to Modified Chinese criteria, sites which are classified as not susceptible to liquefaction, experienced significant bearing capacity failures and settlements due of liquefaction of the fine grained (or cohesive) soils.

2.2 Andrews and Martin (2000)

After re-examining the database provided by Wang (1979), Andrews and Martin (2000) re-evaluated the Modified Chinese criteria. They also used the data obtained from earthquakes occurred in succeeding years. They suggested that fine grained soils have liquefaction triggering potential if (i) percent of fines by weight smaller than 0.002 mm is less than 10% and (ii) LL is less than 32. According to these criteria, soils satisfy the only one of these conditions required further testing and ones they do not meet any of these conditions are not vulnerable to liquefaction.

Andrews and Martin (2000) criteria further decrease the upper limit for LL and re-defined the boundary as 0.002 mm between silt-size and clay-size particles. Additionally they do not consider wc/LL ratio as a screening part for the assessment of liquefaction susceptibility. However, wc/LL parameter of Chinese criteria is stated as the ratio expressing soil sensitivity and differentiating criterion of Chinese criteria by Bray and Sancio (2006). The criteria proposed by Andrews and Martin (2000) also have the same limitations as the Chinese criteria, since they mainly use the same database.

2.3 Seed et al. (2003)

Based on the field observations after 1999 Adapazar and 1999 Chi Chi earthquakes and laboratory test data, Seed et al. (2003) pointed out that higher plasticity soils may be susceptible to significant excess pore water pressure increase and consequent loss of strength than it is determined by using the Modified Chinese criteria. It is also mentioned that while plasticity is increasing, there is a gradual transition in response of soils and high plasticity soils suffer from cyclic shearing to some degree. When plasticity increases as well as the level of shear strain required triggering liquefaction also increases. Contrary to Chinese Criteria and Andrews and Martin (2000), this study stated that the percent of clay-size particle is not important but the activity of clay particles is a important factor and using the latter parameter as a criterion may lead to unconservative conclusions regarding liquefaction susceptibility.

After these discussions, Seed et al. (2003) proposed new criteria for the assessment of liquefaction susceptibility of fine grained soils. These criteria classify soils based on soil index parameters as shown in Figure 2. Soils, which satisfy all three following conditions: (i) PI < 12, (ii) LL < 37 and (iii) wc/LL > 0.8 fall into Zone A and considered to be potentially liquefiable. Soils, which satisfy the following conditions: (i) 12 < PI <20, (ii) 37 < LL < 47 and (iii) wc/LL > 0.85 fall into zone B, are classified to be moderately susceptible to liquefaction and need further testing. Soils lie out of these boundaries (named as Zone C) are not considered to be susceptible to "classical" liquefaction.

This methodology is much more reliable to compare with the Modified Chinese criteria and Andrews and Martin (2000) criteria .This methodology considers mineralogy rather than grain size by setting PI as a parameter for liquefaction. Moreover, Seed et al. (2003) accounts for sensitivity of fine-grained soils by considering wc/LL ratio as a screening tool. However, authors do not clearly address how these criteria were developed. Instead, these criteria were proposed as a summary of their knowledge up to that date, gained from experimental researches and field case histories. Thus, it is not clear under which cyclic loading level these criteria are valid.

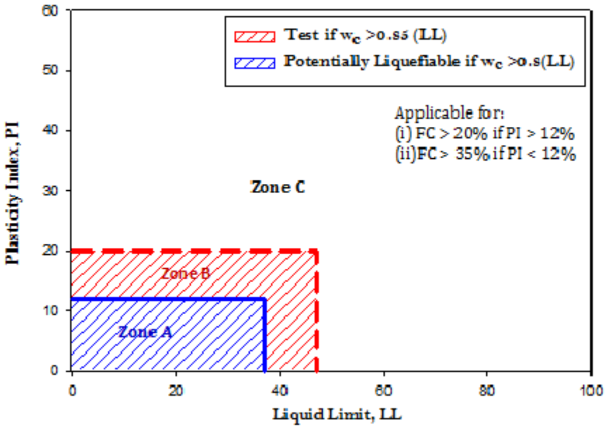

Fig.2: Recommended liquefaction susceptibility boundaries for fine-grained soils by Seed et al. (2003)

2.4 Bray et al. (2004b)

Bray et al. (2004b) criticized Modified Chinese criteria and methodology proposed by Andrews and Martin (2000). Bray et al. (2004b) proposed the criteria after 1999 Kocaeli earthquake, were developed based on more than 100 cyclic triaxial tests (CTX), 24 consolidation tests, 19 shear strength tests and numerous index tests performed on undisturbed specimens obtained from 7 different liquefied sites at Adapazari. Specimens mostly have more than 15% of particles by weight smaller than 0.005 mm and more than 35% of particle by weight smaller than 0.075mm, covering a large range on plasticity index scale (0 < PI <40). CTX tests are performed under undrained conditions at a frequency of either 1 Hz or 0.005 Hz. During CTX tests, one of three CSRs (0.3, 0.4 or 0.5) was applied to specimens. Bray et al (2004b) set number of cycles necessary to reach 3% single amplitude (5% double amplitude) axial strain as acriterion for liquefaction. According to liquefaction susceptibility criteria proposed by Bray et al. (2004b), soils with (i) wc/LL ≥ 0.85 and (ii) PI ≤ 12 are considered to be vulnerable to liquefaction, soils having (i) wc/LL ≥ 0.80 and (ii) 12 < PI < 20 are considered to be moderately susceptible to liquefaction or cyclic mobility and they require further laboratory testing for determination of their actual liquefaction potential. Soils which have PI greater than 20 are considered to be non-liquefiable because of high clay content.

There are various similarities between the criteria of Seed et al. (2003) and Bray et al.(2004b),except LL parameter is a common parameter for all of the previous studies. When Bray et al.(2004b) observed that a number of specimens with LL > 35 found to be moderately susceptible to liquefaction, they dropped LL parameter. Bray et al. (2004b) provides more information about specimens used in their study and methodology of testing such as amplitude of loading (one of three different CSRs of 0.3, 0.4 and 0.5) applied during cyclic tests. However, problems like the ambiguity in the definition of liquefaction and amplitude of loading also exist in this study. A range of nominal CSR's is provided in this study, Rather than a specific CSR level and it gives rise to the same question again: under which loading amplitudes these materials are liquefiable?

2.5 Bray and Sancio (2006)

Bray and Sancio (2006) further modified the criteria proposed by Bray et al. (2004b). In addition to CTX tests, 10 cyclic simple shear (CSS) tests were performed on undisturbed samples of silty and clayey soils obtained from the same sites. These fine-grained soils cover a relatively smaller range of PI (0< PI< 25) and have fines content (FC) generally greater than 70%. Moreover, the standard penetration test (SPT) blow counts, (N1)60, of these soils are in the range of 3 to 8.

According to Bray and Sancio (2006) soils with (i) wc/LL > 0.85 and (ii) PI < 12 are vulnerable to liquefaction, soils having (i) wc/LL > 0.80 and (ii) 12 < PI < 18 are moderately susceptible to liquefaction and they propose further laboratory testing for fine-grained soils located in this range; whereas, soils having PI > 18 are considered to be non-liquefiable under low effective stress levels because of their high clay content. The strain-based liquefaction criterion proposed by Bray et al. (2004b) was adopted by Bray and Sancio(2006) in this study. These criteria are developed by using the same database used by Bray et al. (2004b).

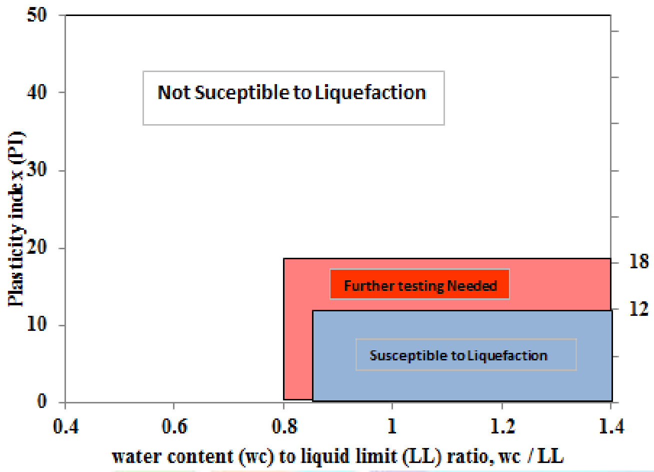

Fig.3: Liquefaction susceptibility margins proposed by Bray and Sancio (2006)

2.6 Boulanger and Idriss (2004, 2006)

Boulanger and Idriss (2004, 2006) discussed the problems observed for the development of liquefaction susceptibility criteria due to difficulties associated with the definition of liquefaction. They have proposed new liquefaction susceptibility criteria based on an extensive literature survey. In that criteria fine-grained soils are classified into following categories as, “clay-like soils” and “sand-like soils”. Sand-like soils are defined as the fine-grained soils, which undergo cyclic liquefaction by exhibiting a response similar to sands; whereas clay-like soils are defined as fine-grained soils which undergo cyclic mobility rather than cyclic liquefaction. According to Boulanger and Idriss (2004, 2006) there exists a smooth transition from sand-like behaviour to clay like behaviour across a range of Atterberg Limits. Fine-grained soils with PI ≥ 7 (PI ≥ 5 for CL-ML soils) are considered to exhibit clay-like behaviour and therefore they are vulnerable to cyclic mobility. On the other hand, fine grained soils with PI values between 3 and 6 are considered to exhibit transient behaviour and therefore further testing is required for soils lying in this range. Soils that do not satisfy any of these conditions are considered to be liquefiable according to Boulanger and Idriss (2006).

Boulanger and Idriss discussed the validity of other parameters such as: Atterberg Limits, water content and clay content used in prior criteria for liquefaction susceptibility. In this regard, similar to Seed et al. (2003) and Bray et al. (2004a, b), Boulanger and Idriss state that clay content criterion, which was previously used in Chinese Criteria and Andrews and Martin (2000), is not proved to correlate well with the engineering properties to reflect liquefaction potential of fine-grained soils. They reported that water content relative to Atterberg Limit value (LL) is a good indicator of cyclic failures in clay-like soils; however Boulanger and Idriss do not considered wc/LL as a good screening tool to identify soil behaviour (sand-like or clay-like) since soils can have high or low ratios of wc/LL depending on the depositional environment. They recommend use of “liquefaction” term for sand-like soils and “cyclic failure” term for claylike soils.

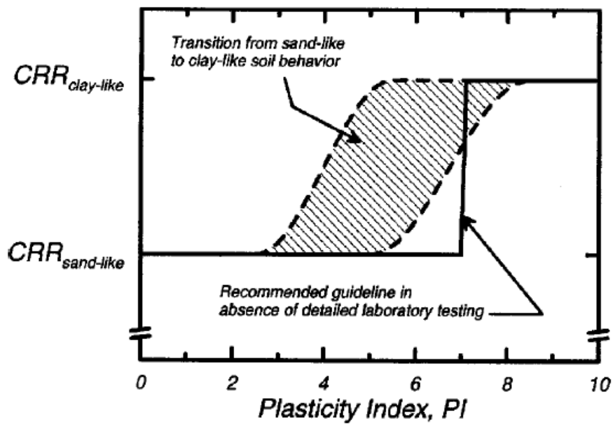

Fig.4: Schematic Illustration of the transition from sand-like to clay-like behavior for fine-grained soils with increasing PI, and recommended guideline for practice. (After Boulanger & Idriss, 2006)

Boulanger and Idriss provide a schematic illustration of liquefaction susceptibility boundary on cyclic resistance ratio (CRR) vs. PI domain (Figure 4). However, it should be noted that, the boundary curve, as illustrated in Figure 4, is not drawn to scale. Even though this study gives an insight regarding the change in liquefaction potential with amplitude of loading, i.e. CSR, still it does not propose a solution for its estimation.

2.7 Other Studies

In addition to previously mentioned studies, there have been numerous efforts to characterize liquefaction susceptibility of fine-grained soils which will be discussed in this section. Youd (1998) proposed that soils having “C” descriptor according to Unified Soil Classification System (USCS) are not vulnerable to liquefaction. Moreover, Youd also provides a screening tool for liquefaction such that fine grained soils lying below A-line with LL < 35 or soils having PI < 7 are considered to be susceptible to liquefaction. Polito (2001) later proposed a liquefaction susceptibility criteria, based on soil plasticity in which he suggested that soils are liquefiable if they have (i) PI < 7 and (ii) LL < 25, they are moderately liquefiable if they have (i) 7 < PI <10 and (ii) 25 < LL < 35, and soils are vulnerable to cyclic mobility if they have (i) 10 < PI < 15 and (ii) 35 < LL < 50. Fine-grained soils lying out of these ranges are considered to be non-liquefiable. Even though Polito

(2001) used parameters to account for the activity of clayey particles, he did not specify the cyclic stress ratio level of the cyclic tests performed. Thus, it is not clear under which seismic loading conditions these criteria are valid. On the other hand, similar to Andrews and Martin (2000), Polito (2001) does not consider wc/LL, which reflects the sensitivity of soils as stated by Bray and Sancio (2006), as a screening parameter to identify liquefiable soils Gratchev et al. (2006) examined the validity of PI as a screening tool for liquefaction susceptibility by performing undrained cyclic stress controlled ring-shear tests on artificial mixtures of saturated soils with varying PI. They found that the liquefaction potential of fine-grained soils without high ion concentrations in their pore-water can be related to PI, such that an increase in PI causes a decrease in liquefaction potential of soil and for PI >15 soils are considered to be non liquefiable. Robertson and Wride (1998) proposed a criterion according to soil type behaviour index (Ic) which can be determined using CPT parameters: normalized tip resistance, Q, and friction ratio, FR. Authors suggest that soils with Ic> 2.6 are considered to be non liquefiable; whereas soils with Ic< 2.6 and FR ≤1.0% are considered to be very sensitive and vulnerable to liquefaction. However, the proposed cut-off value of Ic criticized by some researchers (Gilstrap, 1998; Zhang et al., 2002). They stated that 2.6 is too conservative and this boundary should be lowered. Later Youd et al. (2001) lowered Ic value to 2.4 and stated that soils with Ic> 2.4 should be further tested while soils with Ic< 2.4 are considered to be liquefiable.

Recently, Li et al. (2007) pointed out the deficiencies of the previous Ic - based classification and proposed using a modified soil behavior type index Ic,m, which depends also on pore pressure ratio (Bq). Using a similar database, Hayati and Andrus (2007) also studied the liquefaction susceptibility of fine-grained soils based on CPT data. However, they found that using Ic,m with the boundaries given by Youd et al. (2001) is not consistent with the PI-based criteria of Bray and Sancio (2006).

Thus, they recommended new criteria depending on both Ic and Bq such that soils with Ic> 2.6 or Bq> 0.5 are too clay rich to be liquefiable, soils with Ic< 2.4 and Bq< 0.4 are vulnerable to liquefaction and soils that lie in between these limits are moderately susceptible to liquefaction and need further testing.

3. Conclusions

Existing liquefaction susceptibility criteria for fine-grained soils were discussed within the confines of this paper. Major limitations of the existing liquefaction susceptibility criteria can be summarized as;

1. There is no unique definition of liquefaction and hence, each criterion is developed based on different understandings regarding what liquefaction behaviour is.

2. Previous liquefaction susceptibility criteria do not consider the level of cyclic loading. They do not provide any information regarding the rate and duration of cyclic loading for which these criteria are valid.

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