APPLICABILITY OF EMPIRICAL CRITERIA FOR LIQUEFACTION SUSCEPTIBILITY EVALUATION OF FRASER RIVER DELTA SILT

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ABSTRACT
The applicability of empirically based criteria for liquefaction assessment of fine-grained soils is examined using data from constant volume cyclic direct simple shear (DSS) tests on Fraser River Delta silt. The findings indicate that the accuracy of the measured index parameters such as liquid limit, plastic limit, and moisture content is a pivotal consideration in the use of empirical criteria. The criteria that use plasticity parameters and water content appear to better capture the liquefaction susceptibility of Fraser River silt. Insufficient accounting of the parameters that critically govern the liquefaction susceptibility seems to be a key reason for the observed inconsistencies in the general applicability of empirical criteria. Since laboratory element testing allows capturing the effect of most of the governing parameters, it emerges as the prudent approach for estimating liquefaction susceptibility of fine-grained soils.

RÉSUMÉ
L'applicabilité des critères empiriquement basés pour l'évaluation de liquéfaction des sols fins est examinée en utilisant des données d'essais cycliques de volume constant de cisaillement direct simple sur du silt du delta du fleuve Fraser. Les résultats indiquent que l'exactitude des paramètres d'indice mesurés tels que la limite de liquidité, la limite de plasticité, et le contenu d'humidité est une considération importante dans l'utilisation des critères empiriques. Les critères qui emploient les paramètres de plasticité et la teneur en eau semblent améliorer la capture de la susceptibilité de liquéfaction du silt du fleuve Fraser. La comptabilité insuffisante des paramètres qui régissent critiquement la susceptibilité de liquéfaction semble être une raison principale des contradictions observées dans l'applicabilité générale des critères empiriques. Puisque l'essai de laboratoire laisse capturer l'effet de la plupart des paramètres régissants, il émerge comme une approche prudente pour estimer la susceptibilité de liquéfaction des sols fins.

1. INTRODUCTION

Over the past three decades, significant advance has been made on the understanding of earthquake response of sands while the research undertaken to study the performance of silty sands and fine-grained soils has been limited. The susceptibility of fine-grained soils to liquefaction has been widely evaluated by means of empirical criteria based on index tests. Since the presentation of the empirical "Chinese Criteria" (Wang 1979), several modifications to the criteria have been proposed, and other new index test-based criteria for the evaluation of liquefaction susceptibility of fine-grained soils have also emerged. It has been noted that some fine-grained soils that would classify as non-liquefiable according to some empirical criteria have in fact experienced liquefaction during earthquakes (Boulanger et al. 1998, Bray et al. 2004). An evaluation of data obtained from laboratory cyclic shear testing of silts in British Columbia, Canada, also confirms the limitations of Chinese Criteria as a tool to identify potentially liquefiable soils (Atukorala et al., 2000). As recently noted by Youd et al. (2001), no consensus has been reached on suitable methods for the assessment of liquefaction potential of fine-grained soils.

There is a strong need to undertake laboratory element testing to understand the earthquake response of fine-grained soils in a fundamental manner. In recognition of this, a detailed laboratory testing program is currently underway at the University of British Columbia (UBC) to study the mechanical response of fine-grained silts. The laboratory study includes monotonic and cyclic shear testing using the direct simple shear (DSS) and triaxial devices as well as conventional index testing. As a part of the scope of research, the suitability of currently used empirical criteria for the evaluation of liquefaction susceptibility of fine-grained soils has been examined using a natural silt material obtained from the Fraser River Delta of British Columbia, Canada, and this paper presents the preliminary results from this work.

2. EMPIRICALLY BASED LIQUEFACTION CRITERIA

As presented by Wang (1979), the Chinese Criteria was developed on the basis of observed field performance under earthquake loading to evaluate the liquefaction susceptibility of fine-grained soils. The criteria suggest that soils which satisfy the following conditions would be vulnerable to liquefaction: i) Percent of particles finer that 0.005 mm < 15%; ii) liquid limit (LL) < 35% iii) ratio of water content to liquid limit (w_c/LL) > 0.9 and iv) liquidity index (I_w) ≤ 0.75. If soils that fulfil these conditions plot above the A line in the plasticity chart, the soils may be considered as potentially liquefiable; otherwise, they may be considered non-vulnerable to liquefaction. Finn et al. (1994), after considering the changes due to uncertainties in the measurement of index parameters, proposed the following modifications to the measured properties before applying the criteria: i) decrease fines content by 5%; ii) decrease LL by 2%; and iii) increase w_c by 2%. Considering the differences between the devices used in China and the United States to determine the liquid limit, Koester (1992) also proposed slight changes to the measured values by decreasing the fines contents by 5%, increasing the LL by 1% and decreasing the w_c by 2%. These modified criteria essentially suggest that soils with relatively small fines content are liquefiable, and they call for a narrow range of LL between 33 and 36 as the threshold for liquefaction susceptibility.

Andrews and Martin (2000) have proposed new empirical criteria based on percent of particles finer than 0.002 mm and liquid limit. They emphasize on the importance of the origin of the fine-grained soils, noting that soils such as mine tailings may be susceptible to liquefaction in spite of possessing relatively high clay-size particle content. Andrews and Martin (2000) suggest that soils with percent of particles finer than 0.002 mm < 10% and LL < 32 (LL determined using the Casagrande device) are liquefiable, while soils with percent of particles finer than 0.002 mm > 10% and LL > 32 are not susceptible to liquefaction. They recommend that soils that do not simultaneously satisfy the above two criteria should be further tested to understand the liquefaction susceptibility.

Based on a series of cyclic triaxial tests on sandy soils with different amount of plastic fine contents up to 37%, Polito (2001) presented recommendations for a simplified plasticity-based liquefaction criteria based on the plasticity chart. It was denoted that soils with LL < 25 and plasticity index PI < 7 are "liquefiable", soils with liquid limit between 25 and 35 and PI between 7 and 10 are "potentially liquefiable", and soils outside this boundary in the plasticity chart are "susceptible to cyclic mobility".

More recently, and based on the observations following the Kocaeli earthquake (Turkey) and thorough laboratory work, Bray et al. (2004) have shown that it is the plasticity characteristics, and not the amount of clay-size particles, that best describe the liquefaction susceptibility of fine-grained soils. The proposed criteria by Bray et al. suggest that soils are liquefiable if the plasticity index (PI) is less than 12 and the ratio w_c/LL is grater than 0.85, and that soils are not susceptible to liquefaction if PI is grater than 20 and w_c/LL ratio is less than 0.8. Soils within these two boundaries are considered to have moderate susceptibility to liquefaction and they recommend that laboratory testing be undertaken to clearly determine the potential for liquefaction under cyclic loading.

In general terms, all of the above criteria consider liquid limit as key controlling parameter of liquefaction susceptibility. The Chinese criteria and its later modifications (Wang 1979, Finn et al. 1994 and Koester 1992) as well as Andrews and Martin (2000) criteria consider the amount of clay size particles (percentage smaller that 0.005 mm or 0.002 mm) as an added parameter. Polito (2001) and Bray et al. (2004) criteria, both based in laboratory element testing, suggest that the amount of clay size particles does not play a significant role in the liquefaction susceptibility of fine-grained soils. Chinese criteria and Bray et al. (2004) criteria also suggest that the natural water content (in-situ state) of the soil is also of great importance for the liquefaction assessment while Andrews and Martin (2000) and Polito (2001) consider that it only depends on the mineralogy of the soil in terms of liquid limit, plasticity index, and clay size particles.

3. MATERIAL TESTED AND TEST PROGRAM

The material tested in this study is overbank silt obtained from a site located on the north bank of the South Arm of the Fraser River, in the Fraser River Delta of Richmond, B.C., Canada. This silt material is widely present on the highly populated area of the Fraser River Delta and the understanding of its behaviour under cyclic loading is of significant importance for seismic design works in the region. The Fraser Delta sediments have a thickness of up to 200 m, and generally consist of: overbank silts extending up to 6 m in thickness, overlying up to 20 m in thickness of deltaic sands, which are underlain by a thick deposit of fine sand and clayey silts.

Undisturbed samples were obtained with a specially fabricated tube with no inside clearance, 5-degree cutting edge and 1.4 mm wall thickness. Upon retrieval, the samples were sealed with rubber stoppers and waxed on the ends to maintain the natural water content. The samples were then transported to the Geotechnical Laboratory of the University of British Columbia (UBC) and stored in vertical position in a controlled moist room until extrusion and testing. A tube at a depth of 5.9 m was selected and samples were tested using the NGI-type direct simple shear (DSS) device at UBC (Bjerrum and Landva, 1966). The DSS device is considered to better simulate the cyclic loading conditions presented during an earthquake. The samples tested show silt with very thin (less than 1 mm) interbedded layers of fine sand. Table 1 summarizes the data available from index tests.

Upon extrusion, the samples were carefully trimmed to a diameter of ~70 mm to meet the size of the DSS device using a sharpened-edge polished stainless steel ring. The specimens were also trimmed at the top and bottom of the ring to obtain a height of about 25 mm and water content was obtained from the soil remaining (sides, top and bottom). The observed variation of water content within the samples was less than 2.5%.

Table 1. Index parameters of Fraser River silt.

Index Property	Values
Water content, w_c (%)	37.5
Liquid limit, LL (%)	30.5
Plastic limit, PL (%)	27.3
Plasticity Index, IP	3.2
Liquidity Index, I_w	3.2
% of particles < 0.002mm	10%
% of particles > 0.075mm	13%
Unified soil classification	ML
Specific gravity, Gs	2.69

3.1 Cyclic direct simple shear tests

As described in Wijewickreme and Sanin (2004), DSS testing was conducted using a sinusoidal cyclic shear load, with a frequency of 0.1 Hz, applied at constant cyclic shear stress (τ_{cy}) amplitude. The specimens were normally consolidated to an initial effective stress (σ'_{vo}) of 100 kPa, somewhat higher than the in-situ overburden stress that was estimated to be about 85 kPa.

While a selected strain level is not necessarily an appropriate measure of liquefaction, as an "index" of comparison and for certain discussion purposes, the liquefaction can be considered to have triggered when the single-amplitude horizontal shear strain (γ) in a DSS device reaches a certain value. For the purpose of this study, liquefaction was considered to have occurred when the single-amplitude horizontal shear strain reached 3.75% in a DSS sample, a criterion that has been used in many previous liquefaction studies at UBC. It is equivalent to reaching a 2.5% single-amplitude axial strain in a triaxial sample, which also is a definition for liquefaction previously suggested by the National Research Council of United States (NRC 1985).

The testing indicated that Fraser River Delta silt is susceptible to liquefaction at the tested vertical effective consolidation stress level. Some test results presented in Wijewickreme and Sanin (2004) are reproduced herein to illustrate the observed response. Figure 1 presents a typical result of a cyclic DSS test at a CSR of 0.20, where the sample exhibits contractive behaviour in the first loading cycle and subsequent dilative/contractive response during loading/unloading respectively. Figure 2 presents the response in terms of cyclic stress ratio (CSR $= \tau_{cy}/\sigma'_{vo}$) versus number of cycles.

Cumulative excess pore water pressure in the samples increased with increasing number of loading cycles. Specimens eventually experienced zero, or near zero, transient vertical effective stress conditions during cyclic loading, which is essentially the "cyclic mobility type" response that has been well observed during laboratory research on the undrained cyclic shear response of sands. The stress-strain response clearly indicated the association of the overall reduction of shear modulus with the development of excess pore water pressure. Fraser River silt experienced significantly large permanent cyclic shear strains under moderate levels of cyclic loading which is an important consideration from an engineering design/performance point of view (e.g. γ = 12 to 13% in 11 cycles of CSR = 0.2).

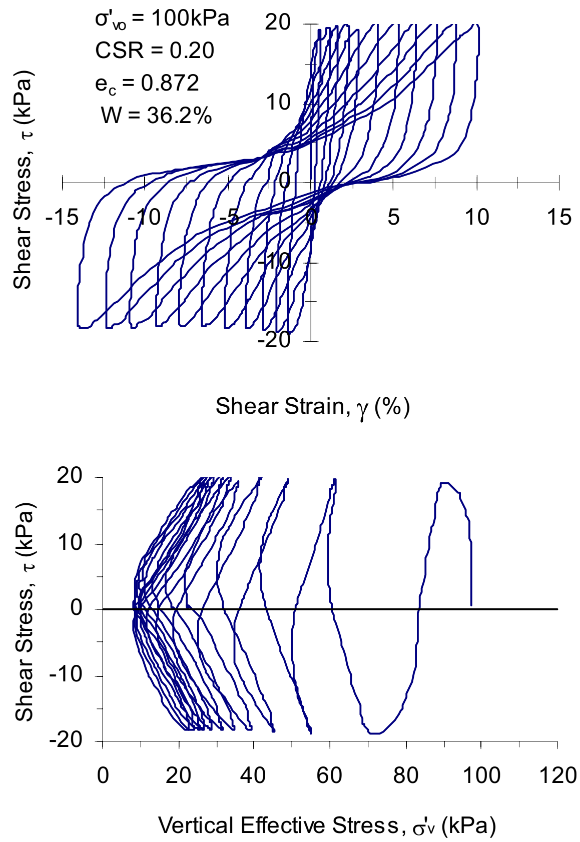

Figure 1. Stress-strain response and stress path during constant volume cyclic DSS loading of Fraser River silt; CSR=0.20 (after Wijewickreme and Sanin 2004).

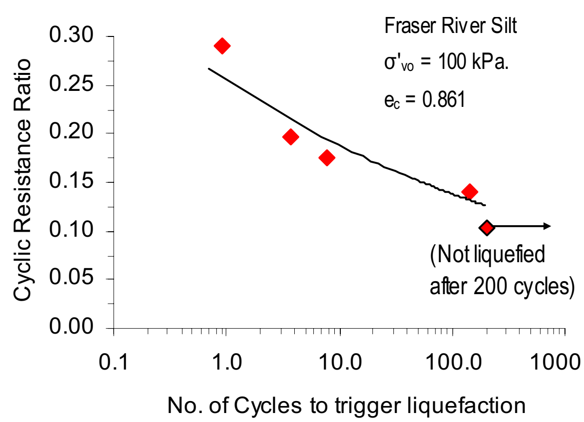

Figure 2. Cyclic resistance ratio versus number of cycles to trigger liquefaction from cyclic DSS tests on Fraser River silt (After Wijewickreme and Sanin 2004).

4. VALIDITY OF EMPIRICAL CRITERIA FOR LIQUEFACTION SUSCEPTIBILITY EVALUATION OF FRASER RIVER SILT

The ready availability of the data from DSS testing provides an opportunity to check the validity of the empirically based criteria in the evaluation of liquefaction susceptibility of Fraser River silt as described below.

Figure 4 shows the Chinese Criteria (Wang 1979) as presented by Seed et al. (1983), and graphically represented by Marcuson et al. (1990). The index parameters for the tested Fraser River silt are also plotted in the same figure along with the suggested modifications proposed by Finn et al. (1994) and Koester (1992). With an LL of 30.5, and percent finer than 0.005 mm of 16%, with respect to the criteria presented by Wang (1979), the Fraser River silt plots essentially on the boundary that defines susceptibility to liquefaction. The modified criterion of fine contents proposed by Finn et al (1994) and Koester et al. (1992), would classify the silt as susceptible to liquefaction.

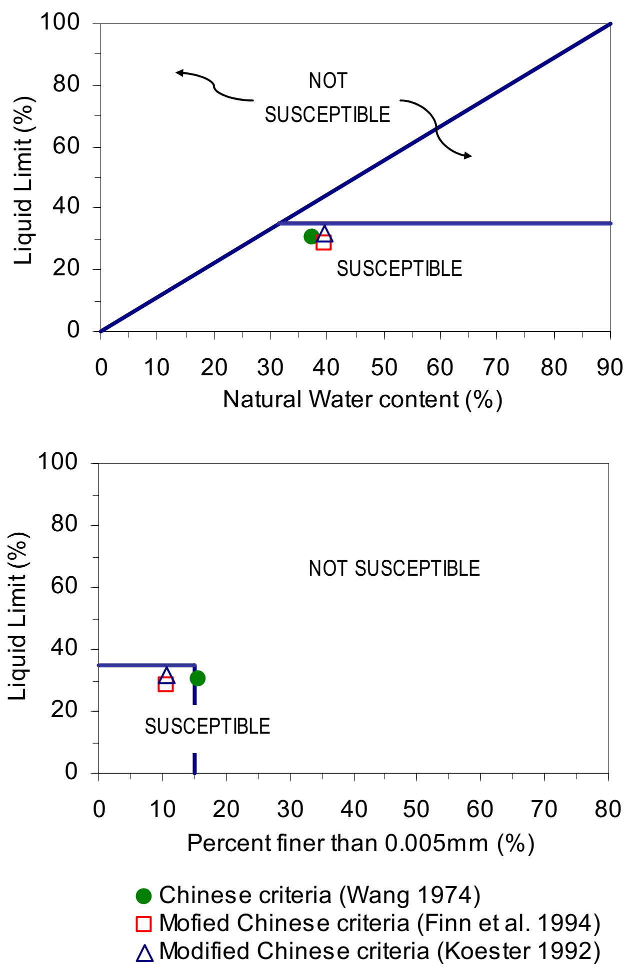

Figure 4. Applicability of Chinese criteria (Wang 1979, Finn et al. 1994, Koester 1992) for liquefaction assessment of Fraser River Delta silt.

In relation to Andrews and Martin (2000) criteria, and given that the criterion of LL = 32 is very close to the Fraser River silt LL = 30.5, again, the sample plots in the boundary between susceptible to liquefaction and further testing required for soils with low plasticity but high clay size particles content. Figure 5 shows a graphical representation of applicability of Andrews and Martin criteria to Fraser River silt.

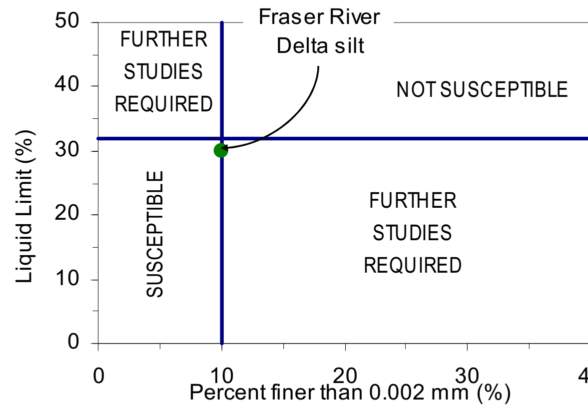

Figure 5. Applicability of Andrews and Martin (2000) criteria for liquefaction assessment to Fraser River Delta silt.

Polito (2001) criteria for liquefaction assessment, when applied to Fraser River Delta silt, show that the index properties would place the Fraser River silt on the "potentially liquefiable" zone as shown in Figure 6. Polito's approach allows the plasticity chart to give an indication of the likelihood of liquefaction, regardless the in-situ state of water content. He has noted that Chinese criteria (Wang 1979, Finn et al. 1994 and Koester et al. 1992) criteria for water content were applicable to the tests performed on his study, nevertheless, the water content was not included in the recommended parameters to assess liquefaction.

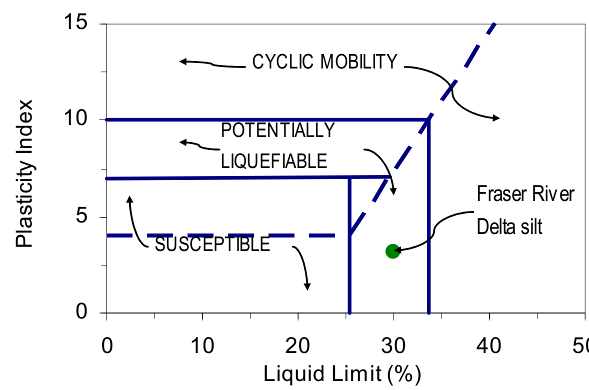

Figure 6. Applicability of Polito (2001) plasticity based criteria for liquefaction assessment to Fraser River Delta silt.

Bray et al (2004) criteria, presented in Figure 7 along with the Fraser River Delta silt index parameters, clearly classifies Fraser River silt in the zone for the soils susceptible to liquefaction.

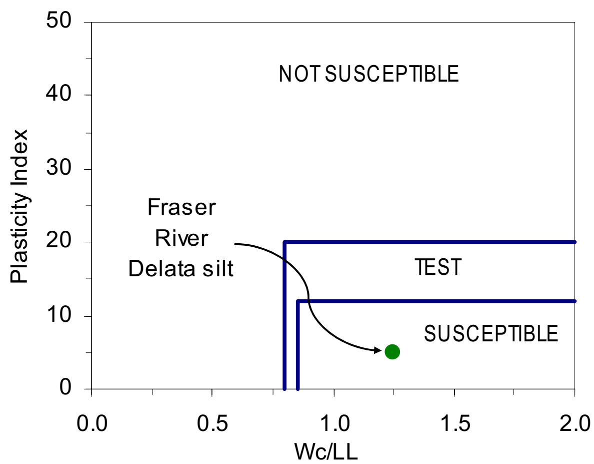

Figure 7. Applicability of Bray et al. (2004) criteria for liquefaction assessment to Fraser River Delta silt.

5. DISCUSSION & CONCLUSIONS

The applicability of empirically based criteria for liquefaction assessment of fine-grained soils was examined considering data from constant volume cyclic direct simple shear (DSS) tests on Fraser River Delta silt. The DSS test results clearly indicate that, on the basis of strain development (see Section 3), Fraser River silt is liquefiable when subjected to a certain threshold number of cycles of a given cyclic shear stress.

Bray et al. (2004) criteria that determine the liquefaction susceptibility based on plasticity and in-situ moisture content (i.e. void ratio) clearly classify Fraser River silt as liquefiable. Polito (2001) criteria, which are based only on plasticity and without including moisture content, place Fraser River silt in the "*Potentially Liquefiable*" zone. The original Chinese Criteria (which use plasticity characteristics, fraction of clay size particles, and moisture content as parameters) provide borderline classifications for the liquefaction susceptibility of Fraser River silt. After modifying the measured index parameters as proposed by Finn et al. (1994) and Koester et al. (1992), the modified Chinese criteria classify Fraser River silt as liquefiable. Andrews and Martin (2000) criteria, which is based on plasticity characteristics and fraction of clay size fraction, do not provide a conclusive assessment since the parameters for the Fraser River silt are located in close proximity to the zone boundary between "*Susceptible to Liquefaction*" and "*Further Studies Required*".

In an overall context, the results from cyclic shear tests suggest that the empirical criteria that use plasticity parameters and water content (e.g. Bray et al. 2004) has a better ability to capture liquefaction susceptibility of Fraser River silt. However, as noted previously by others (Boulanger et al. 1998, Atukorala et al., 2000), the present evaluation confirms that the liquefaction susceptibility assessed using empirical criteria can sometimes lead to incorrect or non-conclusive determinations. In the assessment of the liquefaction susceptibility of a given soil, the accuracy of the measured index parameters (such as liquid limit, plastic limit, and moisture content) becomes a critically important factor especially when the parameters lie close to classification boundaries in empirical criteria. For example, in-situ water content may be affected during sample retrieval, handling, and preparation of test specimens. During the testing of Fraser River silt, the authors have noted that changes in moisture content in the order of 4% can easily take place during handling and exposure to atmosphere. Moreover, the liquid limit and plastic limit measurements conducted at the UBC laboratory for Fraser River silt, when compared with those from an independent laboratory indicated differences in the order of ± 3%.

The mechanical properties and response of soils are controlled by many factors such as mineralogy, grain size/shape, plasticity, particle arrangement (fabric), micro-structure, packing density, confining stress level, age, etc. (Leroueil and Hight 2002). With respect to earthquake loading, the liquefaction susceptibility is also governed by the level of loading (e.g. cyclic ratio and number of cycles as shown in Figure 2 for Fraser River silt). In addition, the level of initial shear stress, commonly referred to as "initial static shear bias" is another important consideration. As shown in Table 2, the current empirical criteria do not consider many of the above parameters that critically govern the liquefaction susceptibility. While the satisfaction of certain conditions with regard to soil parameters selected for empirical criteria can be argued to be *necessary*, it is apparent that this accordance alone may not be *sufficient* to describe the undrained response of a given fine-grained soil. In other words, compliance of LL, water content, % of finer particle fraction, etc. with certain limiting criteria may be a necessary condition for a fine-grained material to be susceptible to liquefaction. However, the observation of such compliance alone for a given material may not be sufficient to deduce that the material is liquefiable, particularly when it is clearly known that there are several parameters outside the above selection that will potentially affect the undrained response of soils.

It is the authors' opinion that this insufficiency of selected parameters is a major reason for the observed inconsistencies in the general applicability empirical criteria to evaluate liquefaction susceptibility of fine-grained soils. Although empirical criteria may be a good indicator of the likelihood of a fine-grained soil to liquefy, it is clear that laboratory element testing that allows capturing the effect of most controlling parameters still remains the prudent approach for estimating liquefaction susceptibility.

Table 2. Factors controlling the response of soils to cyclic loading and their consideration by different empirical criteria for liquefaction assessment.

Factors \ Criteria	Chinese criteria [1]	Andrews and Martin (2000)	Polito (2001)	Bray (2004)
Mineralogy / plasticity	Yes	Yes	Yes	Yes
Grain size	Yes	Yes	No	No
Packing density	Yes [2]	No	No	Yes [2]
Microstructure	No	No	No	No
Fabric	No	No	No	No
Age	No	No	No	No
Confining stress level	No	No	No	No
Level of cyclic loading	No	No	No	No
Initial static shear bias	No	No	No	No

[1] Wang (1976), Seed et al. (1983), Finn et al (1994), Koester (1992)
[2] In terms of water content.

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