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Overview of screening criteria for liquefaction triggering susceptibility

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ABSTRACT: The occurrence of liquefaction has been documented in most major earthquakes for centuries, with earnest efforts to develop systematic engineering approaches for evaluating the phenomenon starting in the 1960s. After five decades of field, laboratory, and numerical studies, debates still persist on formulating a succinct definition of “liquefaction” and correspondingly on distinguishing what soils are susceptible to “liquefaction.” The focus of this paper is a review of the current state of practice of screening criteria for liquefaction triggering susceptibility, primarily criteria used in the United States, China, Japan, and New Zealand. The reviewed screening criteria are based on geologic age, shear wave velocity, grain size distribution, water content, Atterberg limits, and CPT indices. The various criteria can result in conflicting conclusions about liquefaction susceptibility for some soils, while yielding similar conclusions for other soils. Accordingly, additional research is required to reconcile the differences in the criteria and to determine which, if any, should be recommended for practice.

1 INTRODUCTION

The focus of this paper is the review of the current state of practice of screening criteria for liquefaction triggering susceptibility of soils (i.e., “What soils are susceptible to liquefaction triggering?”). It is widely recognized that liquefaction triggering is a function of “compositional” and “environmental” factors of the soil (e.g., Mitchell & Soga 2005), as well as of the imposed loading’s characteristics. However, the screening criteria discussed herein are limited to compositional and environmental factors of the soil, and not the characteristics of the imposed loading which constitutes the next step in evaluating liquefaction potential (i.e., determining the factor of safety against liquefaction triggering or the probability that liquefaction will be triggered for a given earthquake scenario or for a range of scenarios).

Review of literature shows that the primary compositional and environmental factors that influence liquefaction triggering susceptibility of soil are (in no specific order): mineralogy, shapes and size distribution of particles, density, fabric, effective confining stress, and saturation. A multi-tiered screening approach is commonly used in evaluating liquefaction triggering hazard, wherein one of the top tiers often entails determining the mineralogy, grain size distribution, geomorphology, and geologic age of strata in a soil profile. The evaluation method of each of these factors can range widely from project to project and simply could entail use of empirical correlations with in-situ test indices (e.g., cone penetration test (CPT) tip resistance (q_c) and sleeve friction (f_s)) or could be much more involved, entailing detailed geologic studies and geotechnical sampling and laboratory testing (e.g., grain size distribution, water content, and Atterberg limits). Post-earthquake observational data and/or geotechnical laboratory parametric test data provide a basis for developing empirical screening criteria which are most commonly utilized to evaluate the results of these efforts. It is these criteria that are outlined below, with particular emphasis on criteria used in the United States of America (USA) and to a lesser extent criteria used in Japan, New Zealand, and China.

2 GEOLOGIC AGE AND ORIGIN

Geologic age and origin of the soil has been long recognized as having a significant influence on its susceptibility to liquefaction triggering (e.g., Youd & Hoose 1977). However, this influence has been largely expressed qualitatively (e.g., Table 1), making it difficult to incorporate quantitative metrics in engineering liquefaction hazard analyses (e.g., Semple 2013). However, Section 4.3.3.1 of the Chinese building code (CNS 2001) is an exception, stating that soil is considered non-liquefiable or the consequences of liquefaction need not be considered for Pleistocene deposits for shaking intensities 7 to 9; Moss & Chen (2008) note that Chinese Intensity 7 through 9 is approximately equal to Modified Mercalli Intensity VI through X.

The time since last disturbance has been shown to be more relevant to liquefaction triggering susceptibility than geologic age (Hayati & Andrus 2009; Andrus et al. 2009). The two are the same only if the deposit has not been significantly disturbed since deposition (e.g., if liquefaction has not been triggered in the deposit during a previous earthquake). To assess time since last disturbance, Andrus et al. (2009) proposed using the ratio of measured to estimated shear wave velocities (MEVR) where the estimated shear wave velocity is correlated to penetration resistance. The MEVR index was related to increased liquefaction resistance.

Table 1. Estimated susceptibility of sedimentary deposits to liquefaction during strong seismic shaking (after Youd & Perkins 1978).

Type of Deposit	**General Distribution of Cohesionless Sediments in Deposits**	**Likelihood that Cohesionless Sediments, when saturated, will be Susceptible to Liquefaction (by Age of Deposit)**			
		Modern	Holocene	Pleistocene	Pre-Pleistocene
		< 500 yr	500 yr to 10 ka	10 ka - 1.6 Mya	> 1.6 Mya
(a) Continental Deposits					
River Channel	Locally Variable	Very High	High	Low	Very Low
Floodplain	Locally Variable	High	Moderate	Low	Very Low
Alluvial Fan & Plain	Widespread	Moderate	Low	Low	Very Low
Marine Terraces & Plains	Widespread	---	Low	Very Low	Very Low
Delta & Fan-delta	Widespread	High	Moderate	Low	Very Low
Lacustrine & Playa	Variable	High	Moderate	Low	Very Low
Colluvium	Variable	High	Moderate	Low	Very Low
Talus	Widespread	Low	Low	Very Low	Very Low
Dunes	Widespread	High	Moderate	Low	Very Low
Loess	Variable	High	High	High	Unknown
Glacial Till	Variable	Low	Low	Very Low	Very Low
Tuff	Rare	Low	Low	Very Low	Very Low
Tephra	Widespread	High	High	Unknown	Unknown
Residual Soils	Rare	Low	Low	Very Low	Very Low
Sebka	Locally Variable	High	Moderate	Low	Very Low
(b) Coastal Zone					
Delta	Widespread	Very High	High	Low	Very Low
Estuarine	Locally Variable	High	Moderate	Low	Very Low
Beach - High Wave-Energy	Widespread	Moderate	Low	Very Low	Very Low
Beach - Low Wave-Energy	Widespread	High	Moderate	Low	Very Low
Lagoonal	Locally Variable	High	Moderate	Low	Very Low
Fore Shore	Locally Variable	High	Moderate	Low	Very Low
(c) Artificial					
Uncompacted Fill	Variable	Very High	---	---	---
Compacted Fill	Variable	Low	---	---	---
Definitions: ka = thousands of years ago			Mya = millions of years ago		

The underlying premise of the Andrus et al. (2009) approach is that the measurement of penetration resistance mobilizes large strains that inherently disturb the soil, and is thus less sensitive to aging effects. In contrast, the measurement of shear wave velocities directly in the soil is a small strain measurement and is sensitive to aging effects. Thus, the ratio of directly measured shear wave velocities to those estimated from penetration resistance should provide a correlation to the time since last disturbance. Towards this end, Andrus et al. (2009) found that MEVR increases by a factor of approximately 0.08 per log cycle of time and proposed a correlation relating increased liquefaction resistance to MEVR. Accordingly, "aged" soils are more resistant to liquefaction, but they are still susceptible to liquefaction.

3 GRAIN SIZE DISTRIBUTION, WATER CONTENT, AND PLASTICITY

Liquefaction susceptibility screening criteria based on laboratory properties of soils are presented in this section.

3.1 Chinese Criteria

The first liquefaction susceptibility screening criteria used in the USA for fine-grained soils were the "Chinese Criteria" (Wang 1979). Per Seed & Idriss (1982): "…certain types of clayey materials may be vulnerable to severe strength loss as a result of earthquake shaking. These soils appear to have the following characteristics:

Percent Finer than 0.005 mm:	< 15%
Liquid Limit (LL):	< 35%
Water content (w_n %):	> 0.9 x LL

If soils with these characteristics plot above the A-Line on the plasticity chart, the best means of determining their cyclic loading characteristics is by test. Otherwise, clayey soils may be considered non-vulnerable to liquefaction." Marcuson et al. (1990) graphically represented the Chinese Criteria as shown in Figure 1.

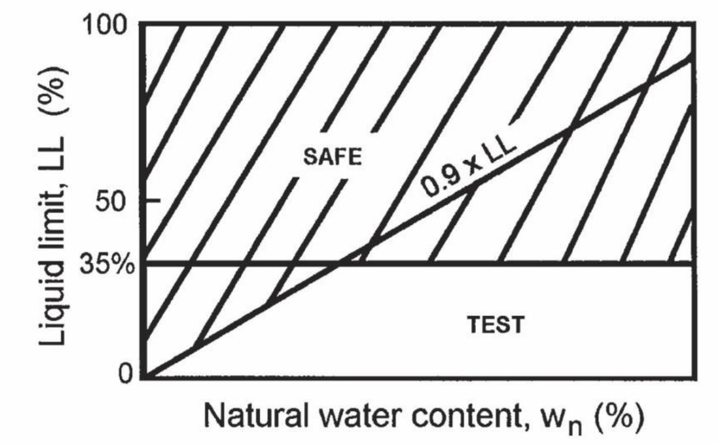


Figure 1. Graphical representation of the Chinese Criteria (from Robertson & Wride 1998; originally by Marcuson et al. 1990).

Based on differences in index tests in the USA and China (Koester 1992), Andrews & Martin (2000) propose modifications to the Chinese Criteria limits (Table 2). Finally, although the above criteria originated in China, Section 4.3.3.2 of the 2001 version of the Chinese building code (CNS 2001) states that if clay fraction is higher than 10%, 13%, and 16% for shaking intensities 7, 8, and 9, respectively, the layer is considered non-liquefiable (with no mention made to LL or w_n). As stated previously, Moss & Chen (2008) note that Chinese Intensity 7 through 9 is approximately equal to Modified Mercalli Intensity VI through X.

3.2 Seed et al. (2003)

Based on post-earthquake observational data in conjunction with subsequent laboratory tests, Seed et al. (2003) propose the criteria illustrated in Figure 2. In this figure, three zones are identified, Zones A, B, and C, which relate to varying degrees of susceptibility to "classic cyclic liquefaction," which they define as the significant loss of strength and stiffness due to cyclic pore pressure generation. They go on to distinguish "classic cyclic liquefaction" (i.e., liquefaction triggering) from "sensitivity," where they define the latter as the loss of strength due to monotonic shearing and/or remoulding as a result of larger, monotonic (unidirectional) shear displacements. In the Seed et al. (2003) criteria, the Plasticity Index (PI) is used in place of the percent clay fines used in the Chinese Criteria, while w_n (or w_c) and LL are still part of the criteria. In the Seed et al. (2003) criteria, only Zone A soils are considered potentially susceptible to liquefaction triggering and can be evaluated using the simplified procedure (e.g., Youd et al. 2001). Soils falling in Zone B may be susceptible to liquefaction triggering, but in many cases cannot be evaluated using the simplified procedure, but rather need to be sampled and tested in the laboratory. Finally, Zone C soils (i.e., soils not plotting in Zones A or B in Figure 2) are generally not considered to be susceptible to liquefaction triggering, but may be sensitive.

Table 2. Modified Chinese Criteria proposed by Andrews & Martin (2000).

	LL[1] < 32	LL[1] > 32
Clay Content[2] < 10%	Susceptible	Further Studies Required (*Considering non-plastic clay sized grains – such as mica*)
Clay Content[2] ≥ 10%	Further Studies Required (*Considering non-plastic clay sized grains – such as mine and quarry tailings*)	Not Susceptible

[1] LL determined by Casagrande-type percussion apparatus

[2] Clay defined as grains finer than 0.002 mm

As opposed to the Chinese Criteria which do not specify applicability as a function of fines content (FC), the Seed et al. (2003) criteria do. Seed et al. (2003) state their criteria are applicable for: FC ≥ 20% if PI > 12% and FC ≥ 35% if PI < 12%. These limits are in line with the "limiting" fines content (FC_L) concept proposed by Polito & Martin (2001) and Thevanayagam et al. (2002). In this context, when FC > FC_L, the coarse grains, if present, "float" in the fine-grained soil matrix, and thus, the behaviour of a soil whose FC is greater than FC_L is distinctly different from a soil whose FC is less than FC_L.

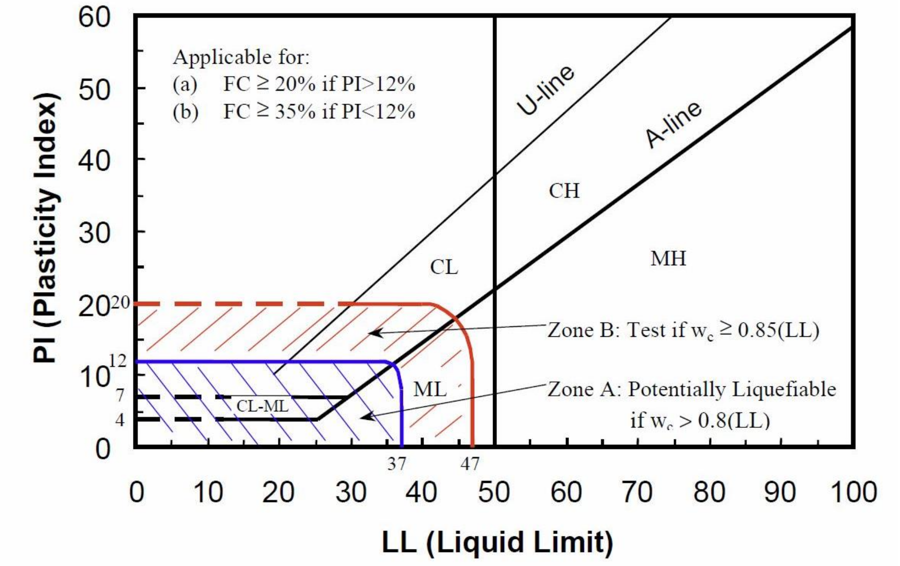


Figure 2. Liquefaction susceptibility criteria proposed by Seed et al. (2003).

3.3 Bray & Sancio (2006)

Also based on post-earthquake observational data in conjunction with subsequent laboratory tests, Bray & Sancio (2006) propose criteria for liquefaction susceptibility of fine-grained soils; their criteria are shown graphically in Figure 3. In this figure, three zones are identified: Susceptible, Moderately Susceptible, and Not Susceptible. Per Bray & Sancio (2006), soils falling in the "Susceptible" zone are considered potentially susceptible to liquefaction triggering, where they default to the definition of liquefaction triggering given by Youd et al. (2001): "Liquefaction is a dramatic loss of strength resulting from increased pore-water pressure and reduced effective stress." Soils falling in the "Not Susceptible" zone are not considered to be susceptible to liquefaction triggering, but may be sensitive (i.e., significant strength reduction upon remoulding). As with the Seed et al. (2003) criteria, the Bray & Sancio (2006) criteria have an intermediate zone between "Susceptible" and "Not Susceptible." This zone is shown in Figure 3 as "Moderately Susceptible." Bray & Sancio (2006) caution that many factors control the cyclic behaviour of fine-grained soils and recommend soils falling in the "Susceptible" and "Moderately Susceptible" zones be sampled and tested to assess their liquefaction susceptibility and strain potential. This is in contrast to the Seed et al. (2003) criteria that imply that the simplified procedure may be used to evaluate the liquefaction potential of Zone A soils, where Zone A soils in the Seed et al. (2003) criteria are somewhat analogous to "Susceptible" soils in the Bray & Sancio (2006) criteria.

Finally, the Bray & Sancio (2006) criteria are based on data for soils that mostly have a FC ≥ 50% (Bray & Sancio 2008), which should be well above the FC_L, regardless of the PI. Accordingly, it should be assumed that the Bray & Sancio (2006) criteria only apply to soils having a $FC \geq FC_L$.

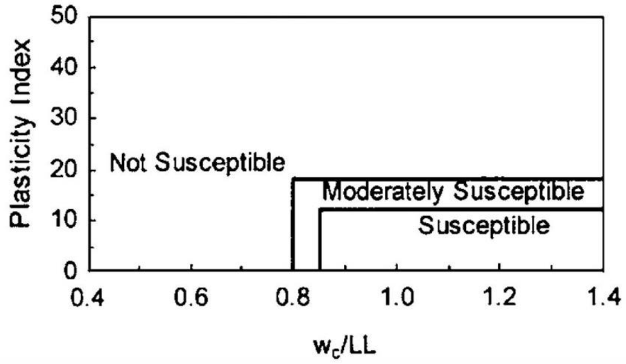


Figure 3. Liquefaction susceptibility criteria proposed by Bray & Sancio (2006).

3.4 Boulanger & Idriss (2006)

The Boulanger & Idriss (2006) criteria, shown in Figure 4, classify soils as "sand-like" and "clay-like" based on PI, with a transition zone between these two categories. The primary purpose of the Boulanger & Idriss (2006) classification scheme is for purposes of determining appropriate testing procedures for assessing cyclic strength (Boulanger & Idriss 2006; Armstrong & Malvick 2014). For soils classifying as "sand-like," the Boulanger & Idriss (2006) criteria state that the simplified liquefaction evaluation procedure is suitable for evaluating the liquefaction potential. On the contrary, soils classifying as "clay-like" should be evaluated using laboratory tests.

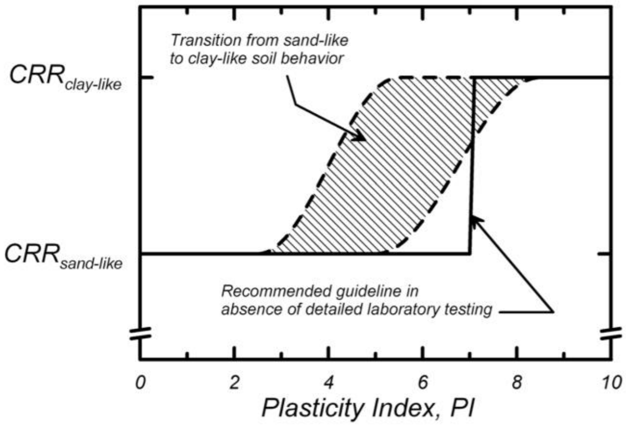
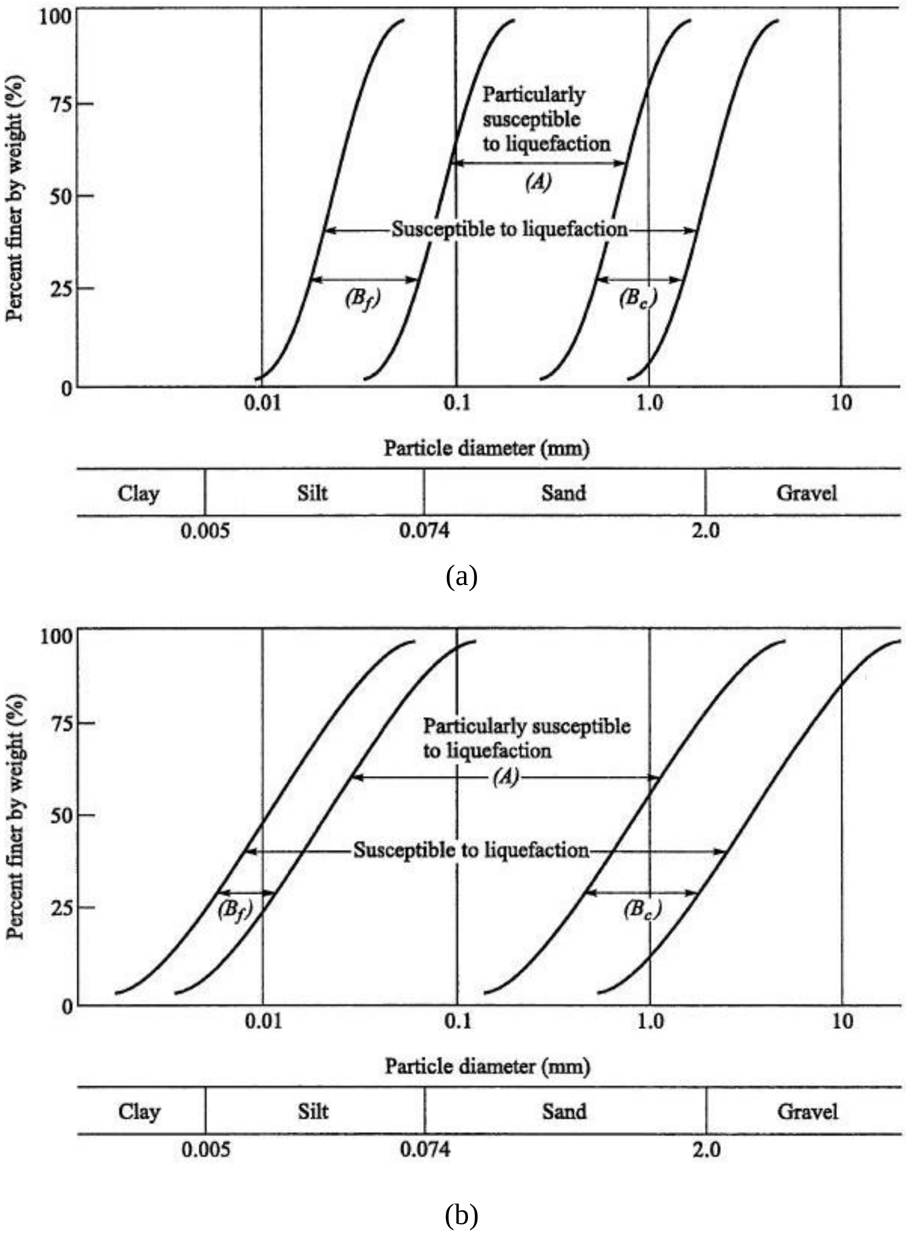


Figure 4. Schematic of the transition from sand-like to clay-like behaviour for fine-grained soils with increasing PI and recommended guideline for assigned cyclic resistance ratio (CRR) proposed by Boulanger & Idriss (2006).

3.5 Japanese Criteria for Port and Harbour Facilities

The Japanese Criteria for liquefaction susceptibility for port and harbour facilities are shown in Figure 5 (Iai et al. 1986, 1989). They are based on post-earthquake observational data supplemented by data from shaking table tests. As may be observed from Figure 5, the criteria for liquefaction susceptibility are solely based on grain size distribution and are still in use (Iai 2013).



(a)

(b)

Figure 5. Japanese liquefaction susceptibility criteria for port and harbour facilities (Iai et al. 1986, 1989): (a) soils having a uniform grading (poorly-graded soils) (i.e., $C_u < 3.5$); (b) well-graded soils (i.e., $C_u > 3.5$). C_u is the coefficient of uniformity.

4 CPT BASED APPROACH

As opposed to laboratory tests, the Robertson & Wride (1998) liquefaction susceptibility criterion is based on the Soil Behaviour Type Index (I_c), which is determined from CPT data. They state that it is reasonable to assume that, in general, soils having $I_c > 2.6$ are not susceptible to liquefaction (Figure 6). However, they recommend that such soils be sampled and evaluated using additional susceptibility criteria (e.g., Chinese Criteria). Youd et al. (2001) lower the I_c sampling and testing threshold specified in the Robertson & Wride (1998) criterion and recommend that soils having $I_c > 2.4$ be sampled and evaluated using additional criteria. The Robertson & Write (1998) criterion (i.e., $I_c > 2.6$) was adopted by the Earthquake Commission (EQC) in New Zealand as the initial liquefaction susceptibility screening criterion for sites in Christchurch (Tonkin & Taylor, 2013).

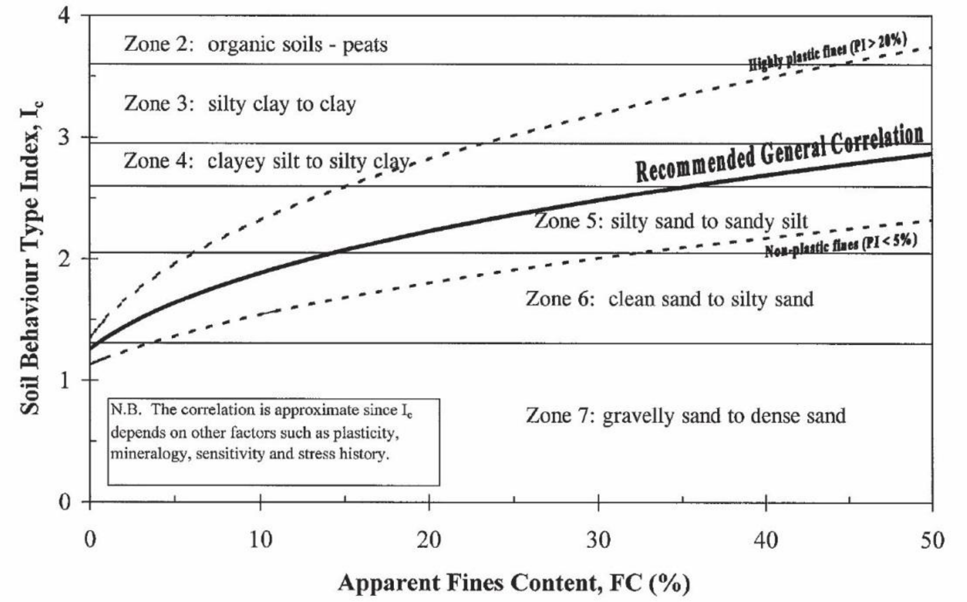


Figure 6. Correlation relating Soil Behaviour Type Index (I_c) and Apparent Fines Content (Robertson & Wride 1998).

5 CONCLUSIONS AND SUMMARY

Various liquefaction susceptibility screening criteria are currently being used in the USA, Japan, China, and New Zealand. The screening criteria reviewed herein are based on geologic age, shear wave velocity, grain size distribution, water content, Atterberg limits, and CPT indices. Inevitably the varying criteria can result in conflicting conclusions about susceptibility for some soils, while yielding similar conclusions for other soils. Accordingly, additional research is required to reconcile the differences in the criteria and to determine which, if any, should be recommended for practice.

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