COMPARING LIQUEFACTION PROCEDURES IN THE U.S. AND CHINA

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ABSTRACT :

Liquefaction is a common occurrence in seismic areas in the United States and China. These countries use different methods to evaluate the potential for liquefaction. This paper compares the standard-of-practice and state-of-the-art analysis methods in both countries to determine the similarities and differences. Results are presented on method compatibility, method disagreement, and what can be learned from this comparison. Of particular importance is how the influence of fines content and/or clay fraction is treated. It is found that "clean" sand triggering curves are in general agreement between the two countries but when sandy soils contain fines the use of clay fraction as a controlling variable is not recommended because it may result in unconservative results.

KEYWORDS:

liquefaction, triggering, clay fraction, fines content, probabilistic

1. Introduction

Liquefaction triggering analysis is treated differently in the U.S. and China. First order similarities are that both countries use a semi-empirical correlation based on previous field case histories of liquefied and non-liquefied sites, and the general shape and curvature of the correlations are similar; concave upwards starting at a CRR (cyclic resistance ratio) just below 0.1. In the U.S. it is common to perform liquefaction triggering analyses using the CPT (cone penetration test) because of the higher accuracy and precision over the SPT (standard penetration test). The CPT methods of Robertson and Wride (1998) and Moss et al. (2006) are respectively the standard-of-practice and state-of-the-art methods currently used for performing deterministic and probabilistic analysis. However, CPT equipment is generally not available in China and the SPT remains the standard *in situ* testing method for liquefaction assessment.

In this paper common SPT methods in the U.S. and China are compared to examine particular differences that may provide insight towards the future of liquefaction engineering in both countries. The SPT method of Cetin et al. (2004) and that reprised in Youd et al. (2001) are compared with Chen and Li (2006), Chen et al (2002), Chen et al. (1991), and the Chinese Building Code (CNS 2001). These methods are chosen to represent deterministic and probabilistic SPT-based method from each country that are frequently used for liquefaction engineering.

For all the similarities in the methods the main difference is how fines, or soil particles smaller than 0.075 mm in diameter, are treated. In China the clay fraction or percentage of particles finer than 0.005 mm is assessed to determine how the fines impact a particular soil's ability to generate excess pore pressures. A version of the so called "Chinese Criteria" is used to screen materials that are not considered liquefiable. In the U.S. the fines content or percentage of particles finer than 0.075 mm is used to determine a soil's ability to generate excess pore pressures. The "Chinese Criteria" was in common use in the U.S. for years, but recent movement away from this towards assessing the plasticity and *in situ* water content has been shown to represent field case histories more accurately.

2. Comparison of "Clean" Sand Curves

Figure 1 shows a comparison of the SPT methods discussed in this paper. These curves are for "clean" sand equivalent conditions where there are no appreciable fines present. The curves are in agreement on the general location of the boundary between liquefaction and non-liquefaction. Cetin et al. (2004) is shown with a probability of liquefaction of 15% which is considered the equivalent of the deterministic threshold. Chen and Li (2006) show a similar equivalence at a probability of liquefaction of 50%.

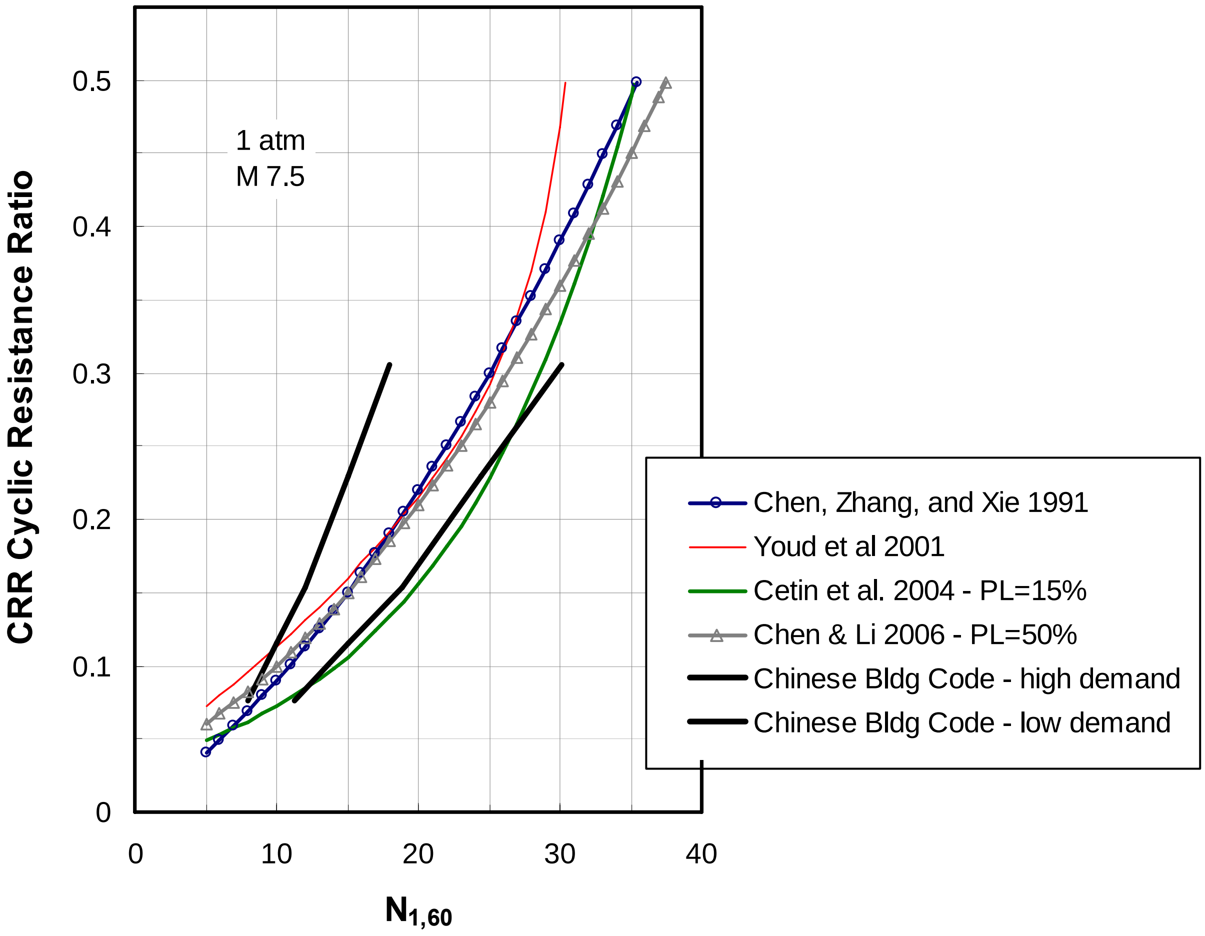


Figure 1. Comparison of U.S. and Chinese "clean sand" liquefaction triggering curves. All curves are shown normalized to 1 atmosphere effective overburden and moment magnitude of 7.5. The curves representing the Chinese Building Code (CNS 2001) have been transformed from critical blow counts (N_{cr}) to CRR boundary curves using a method similar to Chen et al (2002).

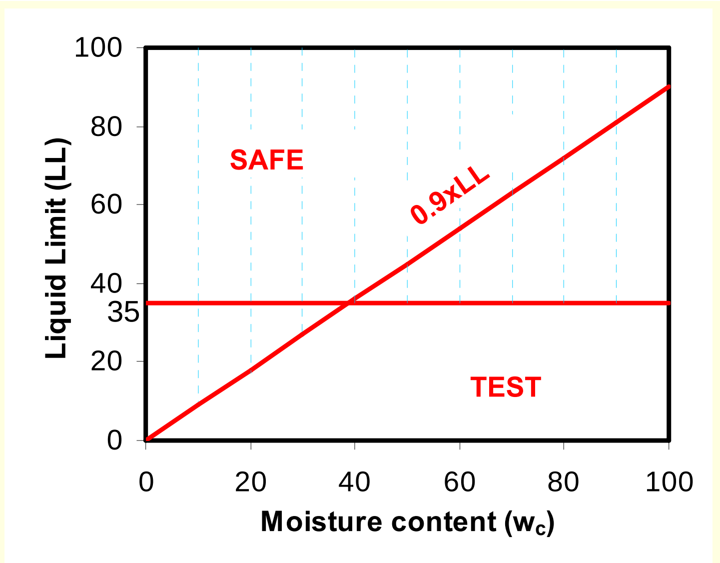
The Chinese Building Code (CNS 2001) is based on two levels of loading (low demand and high demand) and only specifies a critical blow count (N_{cr}) below which liquefaction is considered likely. To compare the Chinese Building Code (CNS 2001) to the other liquefaction triggering curves, the N_{cr} needs to be transformed into a relationship between blow count ($N_{1,60}$) and cyclic resistance ratio (CRR). Chen et al. (2002) first presented the transformation and a similar procedure was used here, the only difference being that the nonlinear shear mass participation factor (r_d) from Cetin et al (2004) was used to hold that variable constant. As shown in Figure 1 the transformed Chinese Building Code specifications do a reasonable job of bounding the threshold range with the high and low demand curves. In a deterministic analysis one can take the range of these curves as a broad but definite boundary between where liquefaction is likely and liquefaction is unlikely. Within the range between these curves is where performance-based engineering is most useful for determining the likelihood of liquefaction with respect to the acceptable level of risk for a given project. The authors feel that Figure 1 demonstrates the convergence of liquefaction triggering analysis for “clean” sand deposits between the two countries. The narrow range over which the curves differ is a function of the nuances of data analysis, curve fitting, and inherent variability of the phenomena of liquefaction triggering.

3. Fines Influence on Liquefaction

The manner in which fines can influence a soil’s ability to generate excess pore pressures is a rather complex physical process and there is some disagreement in the literature as to how best this should be accomplished. Generally there are two effects to account for when discussing field-based liquefaction triggering; 1) the influence of the fines on the soil, and 2) the influence of the fines on the penetration test.

Adding fines to a clean sand will results in the infilling of the void space up to the point where the fines begin to displace the sand grains and dominate the soil matrix. Infilling of the void space in general results in decreased capacity for excess pore pressure due to the reduced void volume and pore fluid available for contractive undrained response. When the sand grains are displaced then the fines dominate the soil matrix and the response to shear stress becomes fines dominated. This discussion has neglected colloidal forces up to this point, focusing on non-plastic fines, but the effect of surface charges can have a great influence on the overall behavior of the soil. Non-plastic fines in a low density state behave in a similar manner to sands, exhibiting contractive response to shear stresses with the propensity for excess pore pressure generation. Plastic fines however will behave in a clay-like manner exhibiting a lesser propensity for excess pore pressure generation and will respond in a cohesive manner. As fines are added to a sandy soil the penetration resistance will decrease due to decreased friction resistance on of the penetration device. Fines will also have a lower permeability than clean sands lending to increased excess pore pressures on the penetration device thereby resulting in lower effective stresses and lower penetration resistance. Both of these effects of fines (on the intergranular soil mechanics and on penetration resistance) are commingled in a field-based liquefaction triggering assessment and are difficult if not impossible to separate.

Regardless of the physical cause and the commingled results, it has been observed that with an increase in fines there is a systematic decrease in the cyclic stress required to liquefy a deposit when measured with penetration resistance. This can be seen in the triggering correlations whether fines content (as used in the U.S.) or clay fraction (as used on China) is the controlling variable used. The procedure for screening out non-liquefiable deposits tends to be the biggest difference in the methods from the two countries. The commonly called “Chinese Criteria” (Figure 2) was introduced following the 1975 Haichang and 1976 Tangshan earthquakes where there was widespread liquefaction of soils with varying fines content and clay fraction. The “Chinese Crieria” defined the liquefaction susceptibility of soil based on the clay fraction (particle size < 0.005 mm), the water content, and the liquid limit. The criteria stipulates that when a soil has a clay fraction greater than 15% the soil is deemed clayey and non-liquefiable.



Percent finer than 0.005 mm	**≤ %15**
Liquid Limit (LL)	**≤ %35**
Water content	**≥ 0.9xLL**

Figure 2. The "Chinese Criteria" after Wang (1979).

The "Chinese Criteria" was generally adopted and used in the U.S. for many years as a reasonable means of identifying non-liquefiable clayey soils. The Chinese Building Code (CNS 2001) uses a slight variation stipulating that if clay fraction is higher than 10%, 13% and 16% for Chinese Intensity 7, 8 and 9 respectively, the layer is considered non-liquefiable. [Note: Chinese Intensity 7 through 9 is approximately equal to Modified Mercalli Intensity VI through X].

The recent 1994 Northridge (U.S.), 1999 Kocaeli (Turkey), and 1999 Chi Chi (Taiwan) earthquakes provided a significant increase in case history data on the liquefaction of soils with varying fines content and clay fraction. Careful analysis of these case histories called into question the use of clay fraction as a means of determining the liquefiability of a material. It has been found in various recent studies that a better indicator of soil behavior is plasticity as measured by the Plastic Index (PI=LL-PL). Soils with fines that exhibit little or no plasticity respond to seismic loading in a manner that is consistent with "clean" sand liquefaction; this is termed sand-like behavior. Soils with fines that exhibit medium to high plasticity respond to seismic loading in a manner that is consistent with cohesive cyclic failure; this is termed clay-like behavior.

Clay-like behavior can result in soil failure and subsequent ground deformations similar to liquefaction but the physics of the soil response is different from liquefaction and therefore requires different testing methods for predicting this behavior. Sand-like behavior and liquefaction potential can be tested in the field using penetration tests. *In situ* testing is most appropriate for identifying liquefaction potential because disturbance effects are minimized by testing the soil in place. Clay-like behavior and cyclic failure potential is more appropriately tested in the lab because sample disturbance of cohesive soils is generally small and lab testing provides more accurate means of measuring the soil response to cyclic loading.

Some recent recommendations on susceptibility criteria for liquefiable soils are presented. In Figures 3, 4, and 5 are shown recommendations by Seed et al. (2003), Boulanger and Idriss (2006), and Bray and Sancio (2006). Recommendations for a threshold between sand-like behavior and clay-like behavior range from a PI of 7 to a PI of 12. The disagreement arises due to the complex response of soils when fines are added and when the plasticity of these fines vary.

There is a large amount of research currently being done both in the lab and in the field to better quantify how fines and plasticity influence liquefaction. The specifics are still debated but there appears to be an emerging consensus that; PI is a good proxy for how plasticity can influence liquefaction, that there exists a fines content threshold above which a soil will behave like the fines and not the coarser matrix soil, and that a criteria based on clay fraction can incorrectly label soils as non-liquefiable when in fact they are susceptible to liquefaction.

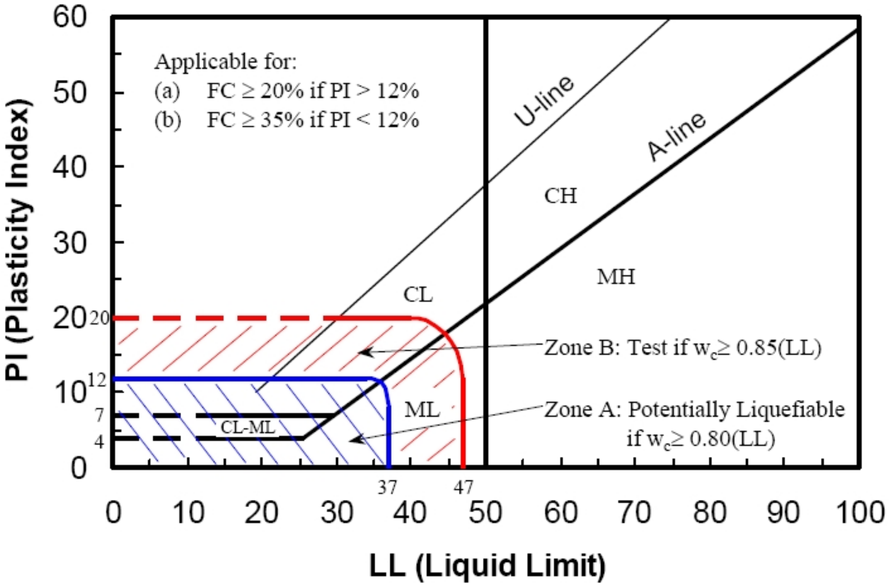


Figure 3 Modified "Atterberg Limits" chart showing recommendations regarding the assessment of soil types considered liquefiable, from Seed et al. (2003).

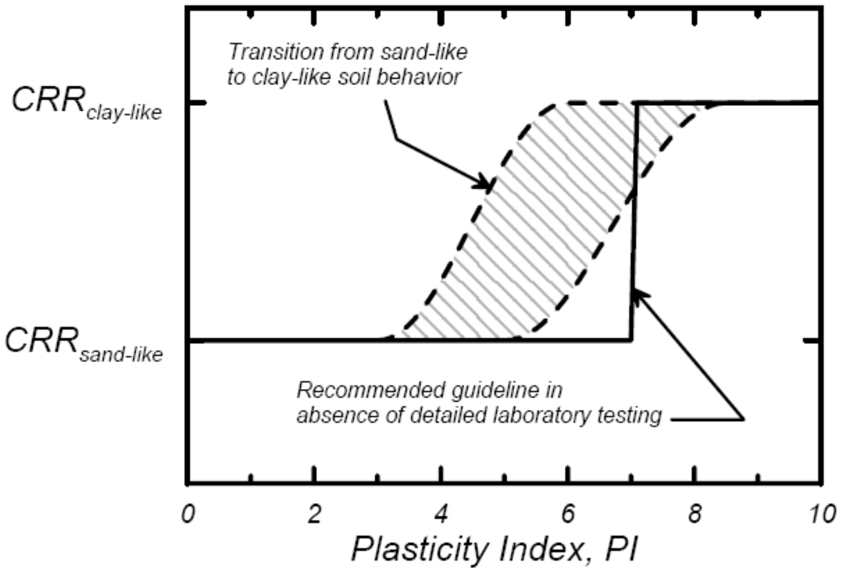


Figure 4. Transition from sand-like to clay-like behavior for fine-grained soils with increasing PI from Boulanger and Idriss (2006)

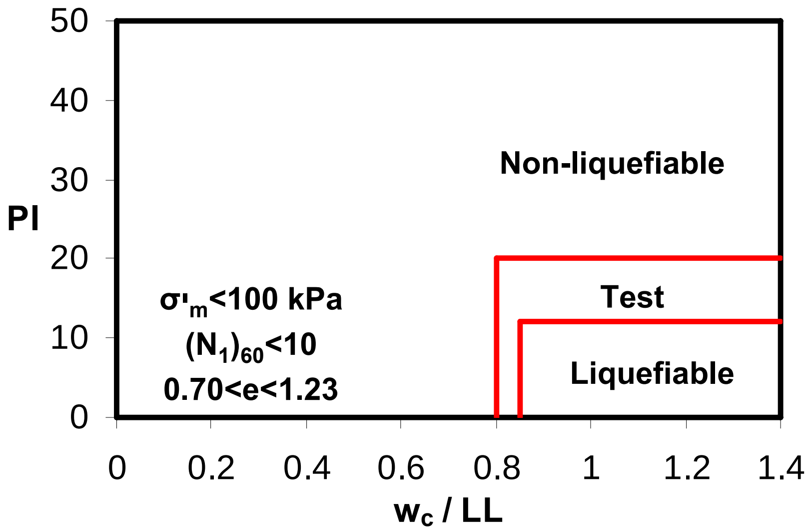


Figure 5, Susceptibility criteria as presented by Bray and Sancio (2006).

4. Comparison of Fines Influenced Curves

If clay fraction is an inadequate indicator of liquefaction susceptibility, this makes the comparison of U.S. and China curves for varying fines content or clay fraction ambiguous. Nonetheless, a rough comparison is made to demonstrate that using clay fraction may be unconservative. Shown is a comparison of U.S. triggering relationships with increasing fines content and Chinese triggering relationships with increasing clay fraction. Figure 6 compares deterministic versus probabilistic relationships from the U.S. and how increasing fines content results in progressive increase in cyclic resistance of the soil. Youd et al. (2001) shows a greater spread in fines content triggering curves when compared with Cetin et al. (2004). This is mainly due to the improved database and reduced uncertainty that was afforded by the Cetin et al. (2004) study. Using U.S. methods the first step of a liquefaction analysis is to determine if the soil is susceptible to liquefaction using one of the screening methods discussed (Figures 3, 4, or 5), and then proceed to a comparison of cyclic load versus cyclic resistance using a correlation (Figure 6). The primary benefit of a probabilistic (as opposed to deterministic) approach is when a performance-based analysis is warranted.

The influence of clay fraction can be seen in the spread of triggering curves as shown (Figure 7). The Chinese Building Code (CNS 2001) states that if clay fraction is higher than 10%, 13%, and 16% for Chinese Intensity 7, 8 and 9 respectively, the layer is considered non-liquefiable. For comparison purposes a fixed clay fraction of 15% was used in this discussion, this is consistent with the "Chinese Criteria" as it was used in the U.S. and is compatible with the application of the Chinese Building Code for higher intensity events. The curves for clay fraction less than or equal to 3% and clay fraction equal to or greater than 15% are shown for both the Chen, Zhang, Xie (1991) study and the transformed Chinese Building Code-high demand (CNS, 2001) recommendations.

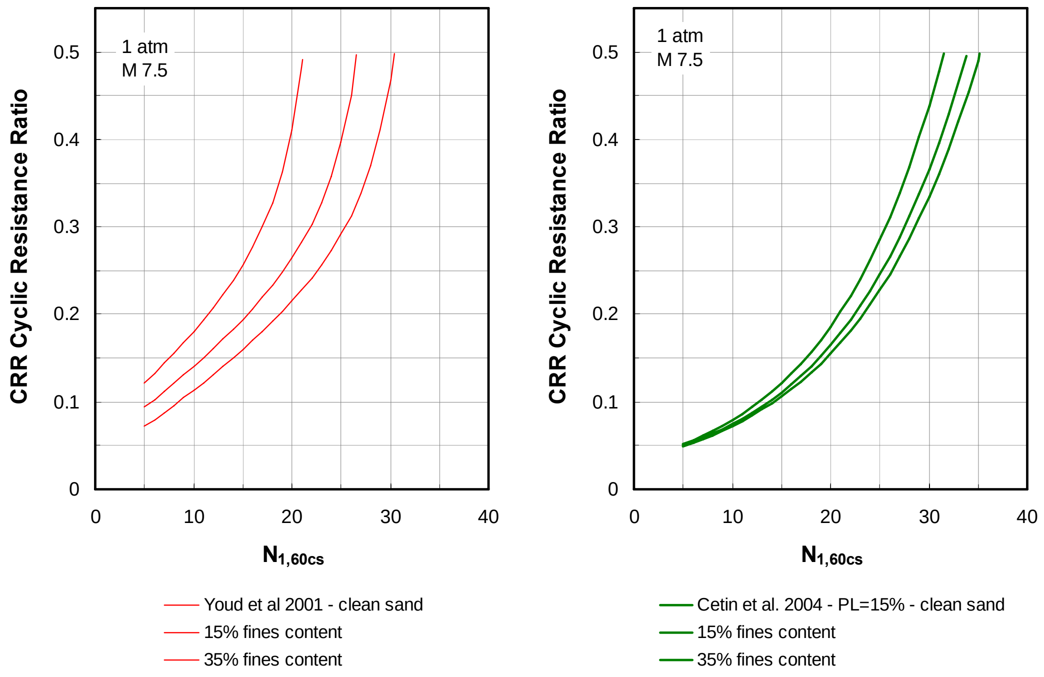


Figure 6 The left curves shows the influence of fines content as recommended by Youd et al (2001), the right curves are those recommended by Cetin et al. (2004). The three curves on each plot show the threshold for soils with FC<5%, FC=15%, and for FC≥35%.

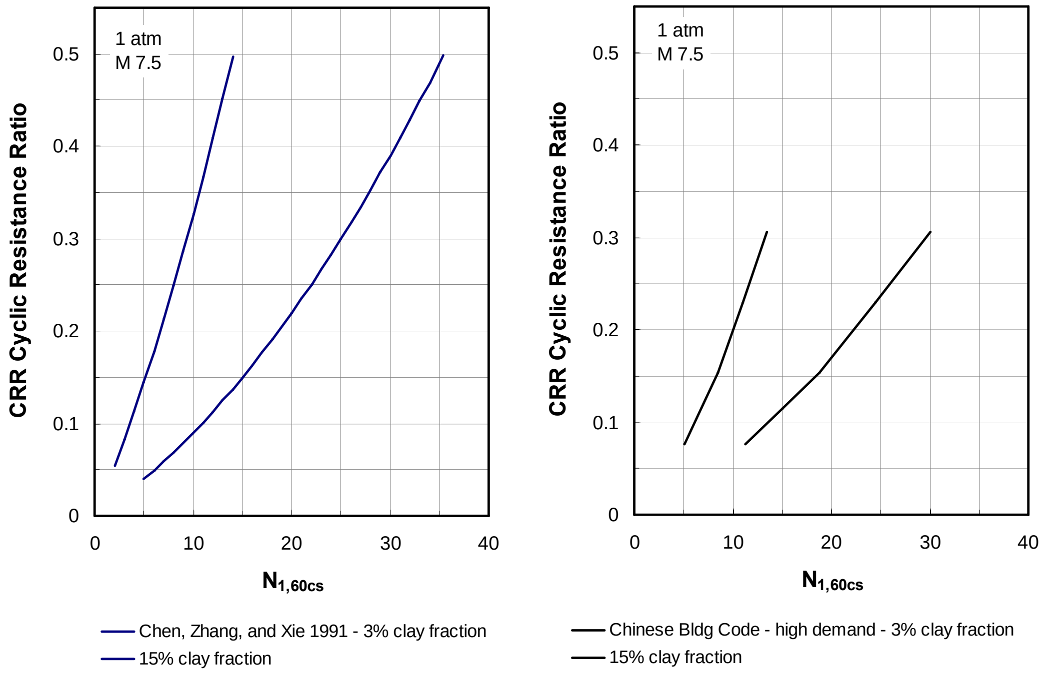


Figure 7 The left curves show the influence of clay fraction as recommended by Chen, Zhang, and Xie (1991), the right curves are those of the Chinese Building Code for high seismic demand (CNS, 2001) as transformed to CRR boundary curves using a method similar to Chen et al (2002). The two curves on each plot show the threshold for soils with less than or equal to 3% clay fraction and for 15% or greater.

The range from a clay fraction of 3% to 15% is large in terms of the change in cyclic resistance afforded the soil. However, as it has been discussed the clay fraction is not the controlling variable, plasticity is, which makes the apparent increase in cyclic resistance undefined. An example of where this would provide problematic results is with a clayey sand that has appreciable clay size fines of low plasticity. Using clay fraction as the primary variable gives a big increase to the cyclic resistance whereas using fines content as the basis would give a comparatively lower cyclic resistance. Using clay fraction can lead to unconservative results. Unconservative results should be avoided in engineering situations particularly when the consequences can be large such as post-liquefaction deformations.

6. Summary and Recommendations

This paper compares liquefaction triggering methods used in the U.S. and China. For “clean” sands it has been shown that there are only minor differences between the triggering thresholds used in the U.S. and that used in China. This general agreement provides consensus for determining when “clean” sands will or will not liquefy given a specific level of cyclic loading.

When, however, fines are present in sandy soil there is disagreement between methods used in the two countries. The U.S. methods examine how fines content (particle size < 0.075 mm) influences the liquefiability of a soil, and soils are deemed non-liquefiable based primarily on the PI (plastic index) of the fines. The exact magnitude of PI is an ongoing point of contention between researchers but it is generally agreed that PI is a controlling variable. The Chinese methods examine how clay fraction (particle size < 0.005 mm) influences the liquefiability of a soil, and soils are deemed non-liquefiable if the clay fraction exceeds roughly 15%.

Recent earthquakes have produced a spate of liquefaction case histories that conflict with the clay fraction criteria. This calls into question the use of the “Chinese Criteria” and clay fraction as a controlling variable. An abbreviated discussion of the mechanics of liquefaction with respect to fines has been presented. Given the current information it is believed that clay fraction is a poor indicator of a soil’s susceptibility to liquefaction and can result in unconservative results for clayey sands with a low plastic clay fraction.

Therefore it is recommended that PI of the fines be used in the screening criteria and not clay fraction. The “clean” sand triggering curves are reasonable for all the methods presented and provide confidence for determining the liquefaction potential for uniform granular soils. For soils with increasing fines the deterministic and/or probabilistic methods from the U.S. are recommended.

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