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# 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, however 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. Of particular importance is how the influence of fines content and/or clay fraction is treated. It is shown 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. The Standard Penetration Test (SPT) is routinely used in both countries and a direct comparison of methods can be made. The Cone Penetration Test (CPT) commonly used in the United States, has recently found more widespread use in China. The benefits of the CPT are discussed and illustrated in a liquefaction case history recently reacquired from the 1976 Tangshan Earthquake.

**Key words:** liquefaction; fines content; clay fraction; probability; SPT; CPT
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Seismic soil liquefaction is defined as earthquake induced significant strength loss in loose saturated granular soils due to excess pore pressure generation and complimentary decrease in effective stress. Liquefaction can cause significant damage to infrastructure during earthquakes and mitigating this hazard is an ongoing effort in seismic areas. Mitigating liquefaction requires; indentifying susceptible soils, evaluating the potential for liquefaction triggering, assessing the post-liquefaction strength with respect to stress conditions, quantifying liquefaction induced deformations (volumetric and shear), and mitigating or designing against these deformations.

Liquefaction triggering is commonly framed as cyclic resistance versus cyclic stress. Cyclic resistance is often measured using a correlated in situ index test because subsurface sampling destroys many of the soil properties that offer resistance against seismic waves. Case histories of liquefaction (and non-liquefaction) from past earthquakes provide the basis for evaluating what cyclic stress conditions cause a soil to liquefy. Cyclic stress if commonly quantified using the simplified method (Seed and Idriss, 1971) to come up with a dimensionless ratio called the cyclic stress ratio (CSR) that accounts for the level of ground shaking and the in situ stress conditions. The cyclic stress at which a soil fails in liquefaction is the cyclic resistance ratio (CRR). Triggering is most likely to occur where CSR = CRR as evaluated from past case histories.

Liquefaction triggering analyses are 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

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liquefaction triggering analyses using the CPT (cone penetration test) because of the higher accuracy and precision over the SPT (standard penetration test). However, CPT equipment is not widely 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), Seed et al (1985) which is reprised in Youd et al (2001), and Idriss and Boulanger (2006) 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 The state of CPT methods in the U. S and China are also discussed The CPT methods of Robertson and Wride (1998) which is reprised in Youd et al (2001), 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 in the U. S A history of CPT use in China is presented and recommendations for future CPT use are presented

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 many years, but recent movement away from this and towards assessing the plasticity and in situ water content has been shown to represent field case histories of liquefaction more accurately.

## 1 Comparison of SPT - Based "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 (< 5%) 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) have a similar equivalence at a probability of liquefaction of 50%.

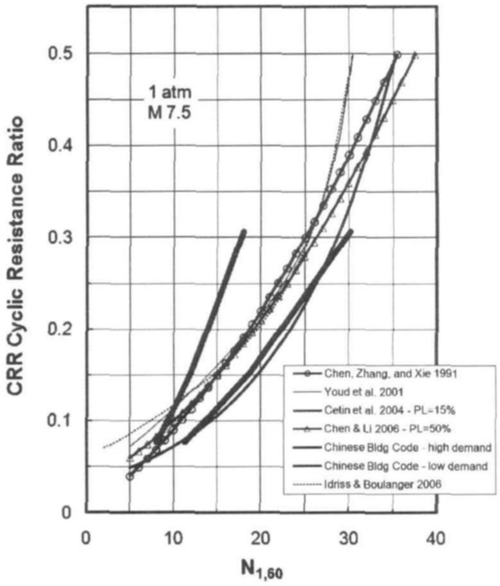


Figure 1 Comparison of U. S. and Chinese "clean sand" liquefaction triggering curves All curves are shown normalized to 1 atmosphere effective overburden and moment magnitude of 7. 5. The curves representing the Chinese Building Code (CNS 2001) have been transformed from critical blow counts ($N_{cr}$) 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 ($N_{1,60}$ the overburden and energy corrected blow count) and cyclic resistance ratio (CRR). Chen et al (2002) first presented this transformation and a similar procedure is 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 reasonably bound 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 range over which the curves differ is a function of the nuances of data collection, data analysis, curve fitting and inherent variability of the phenomena of liquefaction triggering In that range, analysis for a particular project should move past the triggering assessment into a performance-based assessment of potential deformations and the consequences of those deformations (Seed et al 2003).

## 2 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 quantified 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 can behave in sand-like manner, 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 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 stipulate that when a soil has a clay fraction greater than 15% the soil is deemed clayey and non-liquefiable

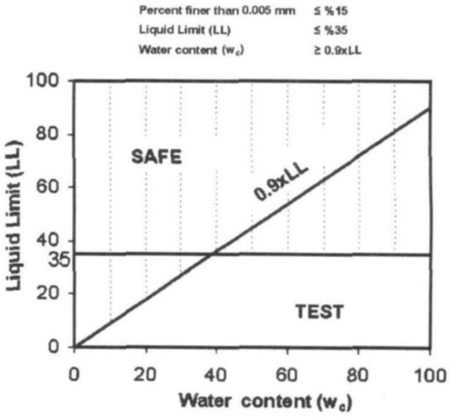


Figure 2 The "Chinese Criteria" after Wang (1979). This was used in the U. S. to determine liquefaction susceptibility until the late 1990's It has since fallen out of use in favor of criteria based on the PI of fines content

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 soil is considered non-liquefiable [Note: Chinese Intensity 7 through 9 is approximately equal to Modified Mercalli Intensity VI through X].

The 1994 Northridge (U. S.), 1999 Kocaeli (Turkey), and 1999 Chi Chi (Taiwan) earthquakes provided a significant increase in case history data on 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 (e g, Chu et al, 2008). It has been found in various recent studies discussed below that a better indicator of liquefiability is plasticity as measured by the plastic index; the liquid limit minus the plastic limit (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.

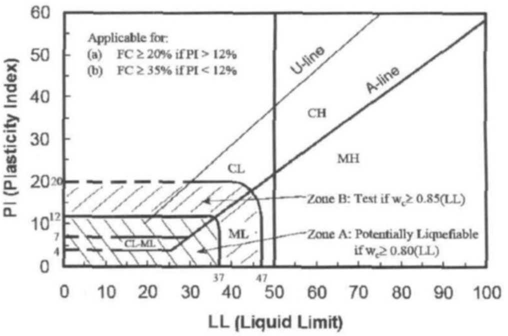
Clay−like behavior can result in soil failure and subsequent ground deformations similar to liquefaction but the physics of the soil response is different from liquefaction and therefore requires different testing methods for predicting this behavior (Boulanger and Idriss, 2006). Whereas sand−like behavior and liquefaction potential is more appropriately tested in the field using in situ penetration tests 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.

As these studies indicate there is a fair amount of research being conducted 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.

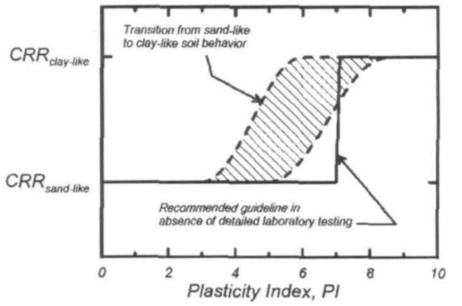
## 3 Comparison of Fines Influenced Curves

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 here 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



**Modified “Atterberg Limits” chart showing recommendations regarding the assessment of soil types considered liquefiable, from Seed et al. (2003).**

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



Schematic illustration of the transition from sand-like to clay-like behavior for fine-grained soils with increasing PI, and the recommended guideline for practice.

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

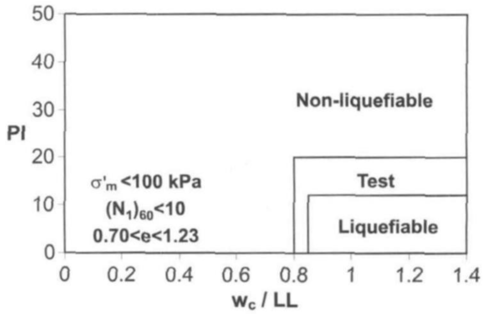


Figure 5 Susceptibility criteria as presented by Bray and Sancio (2006), for the mean effective effective stress less than 100 kPa, the corrected stress less than 100 kPa, the corrected blow count less than 10, and the void ratio between 0. 70 and 1. 23

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 in 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 which 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.

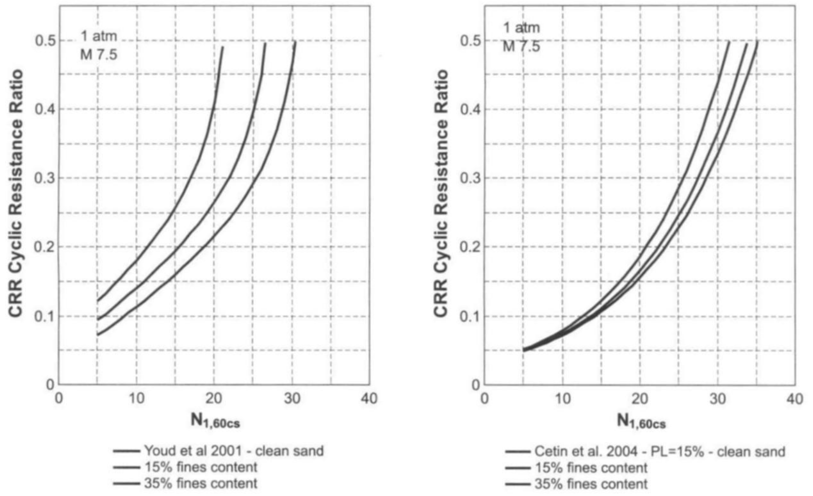


Figure 6　The left curves shows the influence of fines content as recommended by Youd et al (2001), the right curves are those recommended by Cetin et al. (2004). The three curves on each plot show the threshold for soils with FC<5%, FC=15%, and for FC(35%. The denominator is the "clean" sand corrected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

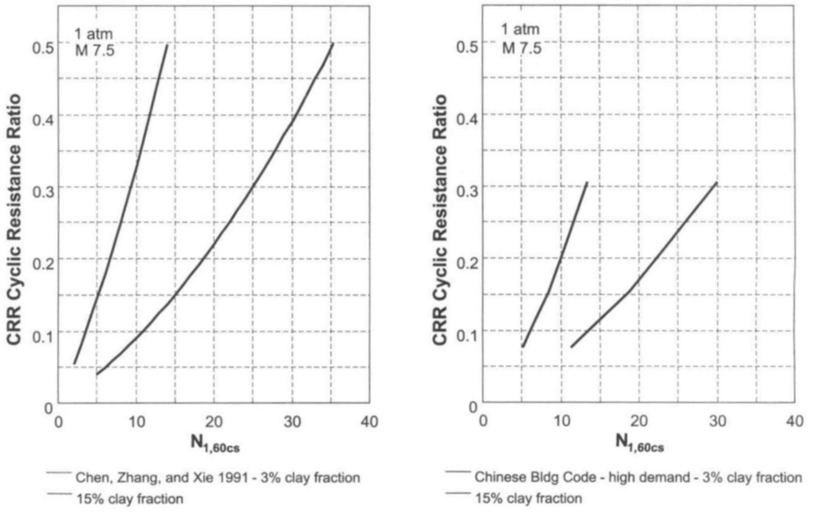


Figure 7　The left curves show the influence of clay fraction as recommended by Chen, Zhang, and Xie (1991), the right curves are those of the Chinese Building Code for high seismic demand (CNS, 2001) as transformed to CRR boundary curves using a method similar to Chen, Hu, and Liu (2002). The two curves 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 predicted in cyclic resistance. 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. If clayey-sand has close to 15% 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. If the clay size fines are then slightly over 15% then it is deemed non-liquefiable by clay fraction but not by fines content. In both cases using clay fraction can lead to unconservative results. Unconservative results should be avoided in engineering situations particularly when the consequences, such as post-liquefaction deformations, can be destructive.

## 4 Discussion of CPT-Based Analysis

The Cone Penetration Test (CPT) has found favor in the U. S. and other parts of the world because the test; produces relatively continuous penetration measurements with depth, is highly repeatable and less prone to operator error, provides more rapid data acquisition than the SPT, and can be accompanied by multiple sensors including the standard sleeve friction load cell, pore fluid pressure transducer, and accelerometer for shear wave velocity in addition to other sensors (Lunne et al. 1997). It is common in the Western U. S. to perform seismic cone testing with pore pressure measurements (SCPTU) to measure the penetration resistance ($q_c$), sleeve friction ($f_s$), shear wave velocity ($V_s$), and pore pressure (u) in each sounding. The tip resistance and sleeve measurements are typically sampled 1 or 5 cm with a 2 cm/sec push rate using a 10 $cm^2$ cone. Pore pressure measurements are made at the same sampling rate and can give a good indication of the location of the water table. An excess pore pressure dissipation test can be performed in which the advance of the cone is stopped until the pore pressures reaches hydrostatic levels giving an indication of the permeability of the soil. The shear wave velocity measurements are typically made every 1 to 1.5 m. The SCPTU provides a relatively complete dataset in a near continuous manner that characterizes soil layering, high- and low- strain soil response, and permeability of individual layers.

The U. S. standard-of-practice in using the CPT for liquefaction triggering assessment was put forth by Robertson and Wride (1998) and can be found summarized in Youd et al. (2001). The recommendations by Youd et al. (2001) focus on using the CPT for "clean" sands because of uncertainty over how to best characterize the influence of fines as measured by the CPT. More recent deterministic methods have been put forth that provide updates on the standard-of-practice (e. g., Idriss and Boulanger, 2006). The U. S. state-of-the-art method can be found in Moss et al. (2006) which presents the results in a probabilistic manner and addresses the influence of fines on CPT measurements and soil liquefiability in a comprehensive manner. Oomen et al. (2010) found that there is little difference in the median prediction rate of the different methods (SPT and CPT), however only probabilistic methods can be used for risk analysis and performance-based engineering as well as provide a bound on the uncertainty of the liquefaction phenomenon.

In China different types of cones have been used since the initial development of CPT in the 1930's. Starting in the late 1960's China developed different cone equipment, standards, and procedures than the U. S. and Europe. In general if a "double bridge" (tip and sleeve equipped) Chinese cone is used following standardized international procedures there appears to be little difference in measurements than those made with a U. S. /European cone (Lui et al., 2010). Therefore there appear to be no compatibility issues when using U. S. /European derived correlations or CPT-based design methods with Chinese cones.

Recent studies have been using SCPTU equipment in various locations around China. An example is the recent collaborative study focused on reacquiring CPT data at sites that were impacted by the 1976 Tangshan Earthquake (Moss et al. 2009; Moss et al. 2011). This collaboration provides a bridge between the methods used in the U. S. and China and for a more comprehensive assessment of in situ soil conditions. Figure 8 shows 1978/1979 SPT and CPT measurements at a site that liquefied during the 1976 Tangshan earthquake (Zhou and Zhang, 1979) with the liquefied layer denoted by a dotted line. Figure 9 shows the 2007 CPT measurements at the same site that include tip, sleeve, pore pressure (not shown), and shear wave velocity. Again the liquefied layer is denoted by a dotted line. The 1977/1978 CPT soundings only measured tip ("single bridge" type cone) and it can be seen show less sensitivity to changes in penetration resistance between soil layers.

Ultimately the goal is to find the best most reliable

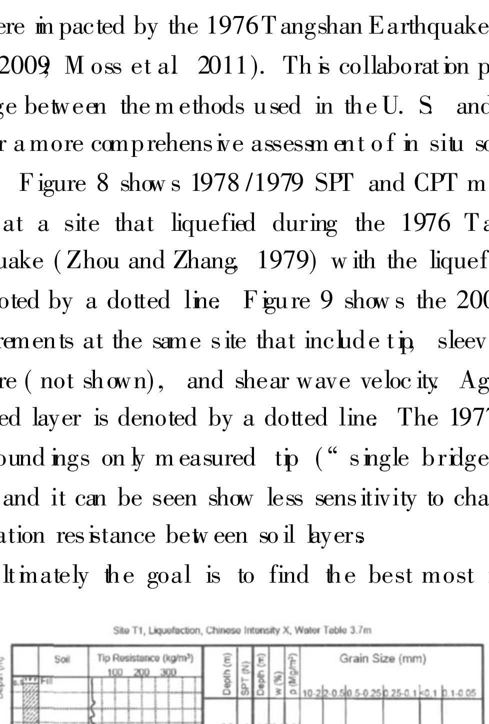


Figure 8 The 1978/1979 investigation (from Moss et al. 2011, after Zhou and Zhang, 1979) was performed using SPT, "single bridge" CPT, and soil samples were retrieved for water content and grain size distribution analysis

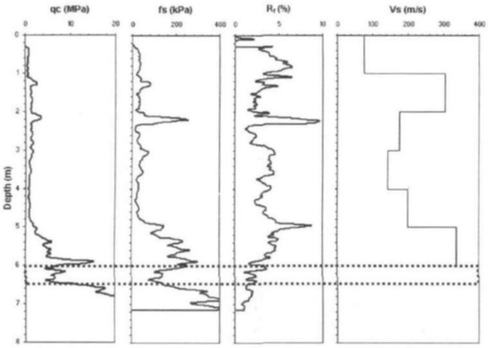


Figure 9 The 2007 investigation was performed using CPT with tip ($q_c$), sleeve ($f_s$), pore pressure ($u$, not shown), and shear wave velocity ($V_S$) from Moss et al. (2011)

methods for assessing the potential for liquefaction. In most projects the authors have found that combining CPT with SPT provides a comprehensive assessment of subsurface conditions. The CPT measures a near continuous profile of tip, sleeve, and pore pressure for use with a triggering correlation. The Vs measurements provide confidence in this assessment by using shear wave velocity based triggering correlations and for use in site response analysis. The SPT can then be used to target particular layers for sampling and lab testing. The SPT blow counts can provide a third check with respect to triggering correlations and the grain size analysis, Atterberg limits, and fines content will provide "ground truthing" to the CPT-based results. In most small to medium sized projects this can be accomplished in 1 to 2 days of in situ testing at a reasonable cost.

## 5 Summary and Recommendations

This paper compares liquefaction triggering methods used in the China and the U. S. For "clean" sands it has been shown that there are only limited differences between the Standard Penetration Test (SPT) based triggering thresholds used in the two countries. This general agreement provides consensus for determining when "clean" sands will or will not liquefy given a specific level of cyclic loading. Where the methods differ is where a project should move beyond assessing triggering and towards a performance-based assessment of potential deformations and the consequences of those deformations.

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 may 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 primarily granular soils. For soils with increasing fines the deterministic and/or probabilistic methods from the U. S. are recommended.

The Cone Penetration Test (CPT) is commonly used in the U. S., less so in China. Comparative studies indicate that there are no substantial differences between "double bridge" cones typically used in China and the electric cone used in the U. S. and Europe. The near continuous readings and consistent results of the CPT as well as the benefit of combining it with pore pressure and shear wave velocity measurements (SCPTU) makes this test very useful for liquefaction studies. It is recommended that the CPT be used more frequently for liquefaction studies in China in conjunction with existing U. S. triggering correlations. A combined investigation using the SPT and CPT provides the most comprehensive assessment of in situ conditions and can result in the best assessment of liquefaction triggering for mitigating this seismic hazard.

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# 美国和中国液化评估程序间的比较

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摘　要: 土壤液化在美国和中国的地震区域频繁发生,然而,两国在评估液化的风险方面方法有所不同。文章比较了两国采用的普遍工程做法和先进的分析方法,并在方法的兼容性、方法的分歧和从这些方法中学到什么这三方面进行总结,尤其是如何处理细屑/粘土粒带来的影响。两国常用的"干净"沙的液化触发曲线基本一致,但是用粘土粒含量作为控制变量的方法可能会导致不保守的结果,因此不推荐使用。标准灌入试验(SPT)是两国都经常使用的研究方法,可直接比较。圆锥贯入试验(CPT)在美国使用普遍,近来在中国也有广泛使用,文章以1976年唐山地震得到的液化案例讨论和说明了应用CPT的优点。

关键词: 土壤液化; 细屑含量; 粘土成分; 概率; 标准贯入实验; 圆椎触探实验