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Relevance and Reliability of Current Liquefaction Criteria

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Abstract

In many parts of the world, including Australia, the state of practice in assessing if liquefaction will occur is based on the recommendations of Youd et al (2001) which arose from workshops convened in the United States by NCEER. The final publication did not so much represent a consensus view as a compromise between conflicting opinions within the expert group. Since then, arguments over key aspects of liquefaction assessment in North America have reached 'a state of chaos' (Youd, 2011).

There seems to be little awareness in Australia of this situation nor appreciation of the NCEER limitations in applying their recommendations. Poorly informed decisions are increasing costs and causing delays to large projects of significance to the national economy.

This paper presents no original research but is an attempt by a practising geotechnical engineer to point out in detail some problematic aspects of the NCEER liquefaction criteria and of current recommendations in the literature. The objective is to encourage other practitioners and regulators to consider reasonable adjustments or alternatives to the de facto standard approach of the NCEER criteria. Some proposals are made in this regard.

Keywords: liquefaction assessment practice, adjustments to NCEER.

1. INTRODUCTION

Assessing liquefaction potential is commonly based on recommendations from workshops held over a five year period by the US National Center for Earthquake Engineering Research or NCEER (Youd & Idriss, 1997; Youd et al, 2001). While the NCEER recommendations are widely viewed as authoritative, the final publication in 2001 was in some respects a compromise between conflicting opinions, which can be discerned from informed comments in the literature (Seed et al, 2001). Since then, arguments and confusion over key aspects of liquefaction assessment in North America have increased resulting in "a state of chaos" (Youd, 2011).

The NCEER approach is based on field evidence of liquefaction, and reflects early developments by the former Professor H.B Seed and his co-workers at the University of California at Berkeley (UC Berkeley). Seed's primary collaborator at UC Berkeley was Professor I.M. Idriss (later UC Davis). Their research initiated from a large earthquake at Niigata, Japan in 1964 (Seed & Idriss, 1967).

The UC Berkeley focus for several years was on the most susceptible type of natural soil. This is recently deposited, clean, uniformly graded sand of fluvial origin; the type which liquefied at Niigata. The "simplified procedure" was developed for characterising the shear stress (expressed as a cyclic stress ratio, or CSR, with the effective overburden stress) from an estimate of the peak ground acceleration at an earthquake shaken site. Sites with documented liquefaction or no liquefaction were represented on a plot of CSR versus the relative density of the weakest layer, and a boundary curve for the critical CSR was drawn to separate these conditions. Seed & Idriss (1971) formalised their procedure using the boundary curve as a criterion for predicting if a site would experience liquefaction. Seed (1979) changed the site characteristic from relative density to the more basic Standard Penetration Test N-value. Numerous earthquake events since the boundary curve development have demonstrated that it is robust.

Subsequently, researchers in Japan and China found sand liquefaction behaviour which did not fit with the boundary curve (Seed et al, 1983). The critical cone penetration test (CPT) tip resistance to avoid liquefaction in granular soil with 60% fines was about half of the comparable value for clean sand. Seed et al (1983) responded by adding less demanding boundary curves for silty sands in the CSR-N space. They also introduced the so-called "Chinese Criteria" for more plastic soils based on classification parameters; fines content, liquid limit and moisture content. Seed & Idriss (1982) and Seed et al (1986) confirmed and refined this extension of their procedure.

The NCEER workshops in the late 1990s endorsed a CPT-based assessment procedure proposed by Robertson & Wride (1998) which has subsequently become widely used by the profession. Youd & Idriss (1997) noted that the NCEER workshop did not reach a consensus on CPT criteria. Professor Idriss took the view that the Robertson & Wride criteria were inadequately developed and that their soil behaviour type index I_c needed further verification. Criticism from the University of California (UC Berkeley and UC Davis) of Professor Robertson's method of recognising the effect of soil type on liquefaction potential has since continued in the literature (Moss et al, 2006; Idriss & Boulanger, 2008). They view Robertson's procedures as significantly unconservative.

UC Berkeley and UC Davis do not agree on the effect of soil texture or type (Youd, 2011). In a quite different approach using Critical State theory, Jeffries & Been (2006) proposed entirely different controlling variables for liquefaction. Space limitations do not permit discussion of their important contribution here, which includes detailed criticism of the empirical approach emanating from California. Currently, a reasonable view of this field is that the application of liquefaction science is far from settled, and that the approach to assessing materials other than recently deposited, clean, uniformly graded sand of fluvial origin is in considerable disarray.

A detailed and well-informed discussion of the NCEER recommendations by Pyke (2003) identified several deficiencies. A major concern over the effect that the NCEER recommendations would have on liquefaction assessment practice was the inadequate qualifiers on the types of soil to which the recommendations could be said to apply. Aspects of Pyke's contribution are included in the discussion below, however Pyke's commentary is essential reading for those involved with liquefaction assessment. A response (published together with Pyke's discussion) attributed to the workshop participants generally agreed with Pyke's comments but nonetheless maintained the utility of the NCEER recommendations. A pivotal assertion in this regard is that application of the NCEER recommendations is more reliable than use of geological criteria. This assertion contradicted earlier recommendations of Kramer (1996), which are discussed later, and also appears to negate restrictions on the site conditions to which the recommendations apply that were stated in the 2001 paper. These restriction have largely been lost in geotechnical practice and the NCEER criteria are often viewed as definitive without qualification.

2. SOIL TEXTURE EFFECTS

4.1 Fines Content

Professor Seed originally formulated the liquefaction boundary curves for clean sand and for sands containing fines using a database of 125 case records from about a dozen earthquake events. An independent review of this database by Fear & McRoberts (1995) found many significant data gaps. They found support for a general observation that sands with fines are more resistant to liquefaction. However, the review did not find support for the more detailed discrimination based on the percentage of fines indicated by Seed et al (1986).

Since the original Seed work, a number of databases have been compiled. The most recent and extensive of these data compilations based on the CPT is at UC Berkeley and it can be downloaded using the link cited in the Moss (2003) reference at the end of this text. Assessment criteria have been presented in

Seed et al (2003) and Moss et al (2006). These papers from UC Berkeley essentially validate the existing NCEER (i.e. Robertson & Wride) boundary curve for “clean sand”. There are however significant differences in their recommended boundary curves for soil containing fines as indicated by Figure 1 replotted from the UC Berkeley publications. A general comparison can be made with the Robertson & Wride (1998) recommendations also included on Figure 1. The variation in soil behaviour type index I_c and CPT friction ratio on Figure 1 nominally represent the same range of soils. A specific comparison can be made by considering a silty sand/sandy silt with a cone tip resistance of 10 MPa and a friction ratio of 0.5% at a depth corresponding to an effective overburden stress of 100 kPa. These parameters give an I_c close to 2.59 and it is apparent that q_{c1N} = 10 MPa is to the right of the relevant boundary curve and the soil is non-liquefiable by the Robertson & Wride (1998) criteria. In contrast, these cone resistance and friction ratio parameters indicate the soil is liquefiable at a cyclic stress ratio greater than about 0.2 by the Moss (2003) criteria.

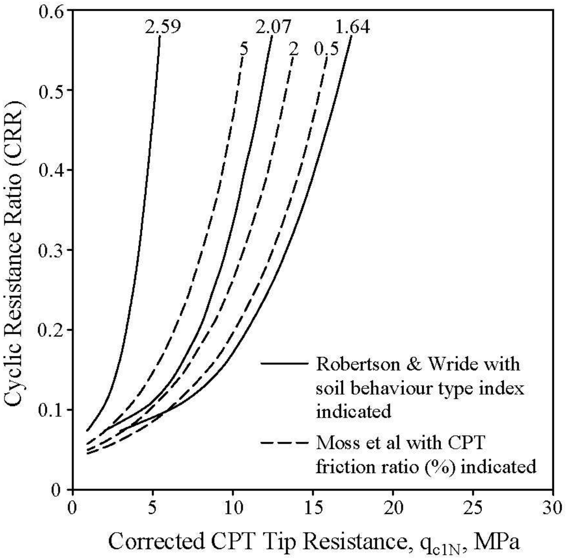

Figure 1: Comparison of Robertson & Wride (1998) and Moss et al (2006) liquefaction boundary curves for granular soils

The reality is that the effects of soil texture on liquefaction potential do not depend only on the quantity of fines in the soil. As noted by Andrews & Martin (2000), silt size particles can be viewed as very fine sand. The grain size boundary between sand and silt is commonly taken at 74 microns which is simply the smallest size that can be seen. There is no necessity for the liquefaction behaviour to change at this grain size. At the time when classification systems were being developed, Glossop & Skempton (1945) pointed out that key behavioural aspects of natural, uniformly graded soils changed in the region of 50 to 60 microns. They placed the lower limit for sand-type behaviour in the coarse silt range. The lower limit corresponded to 80 to 85% finer than 74 microns with up to about 20% of the soil grading to medium silt (< 20 microns). Tsuchida (1970) placed the lower limit for potentially liquefiable soil in the medium to coarse silt range. As noted earlier, a review of the original 1980s UC Berkeley database by Fear & McRoberts (1995) did not find support for Seed’s discrimination of liquefaction resistance based on the percentage of fines. It appears that fines content as a controlling variable should be viewed as an historical expedient that no longer stands scrutiny.

4.2 Fines Plasticity

The significance of fines plasticity has been recognised from the outset in the 'Chinese criteria' discussed earlier. Quantifying the effect of plasticity (colloidal effects) is currently a major research focus and is quite controversial. A considerable part of the disagreement between UC Berkeley and UC Davis, leading to the chaos described by Youd (2011), relates to this issue. Silt blends tested in triaxial compression at UC Davis (Boulanger & Idriss, 2006) exhibited characteristics of sands at PI = 0 and of clays at PI ≥ 4. These results support the view of Boulanger & Idriss (2006, 2007) that there is a rapid transition from sand-like to clay-like behaviour within a range of relatively small PI values. A different conclusion was reached from detailed field and laboratory investigations of fine grained soils which liquefied in the 1999 Kocaeli earthquake by researchers at UC Berkeley (Bray & Sancio, 2006). These studies indicated that fine grained soils with moisture contents close to the Liquid Limit are susceptible to liquefaction especially if they are of low plasticity. PI was found to be an indicator for liquefaction potential rather than a definitive criterion. Following this work, UC Berkeley issued a report prepared by Seed (2010) criticising the Idriss-Boulanger recommendations as unconservative and a hazard to public safety. This debate is currently unresolved.

4.3 Geological Considerations

Unlike artificial soils created in a laboratory, natural soils are subject to geologic processes which govern and constrain their characteristics. Accordingly, there are associations between characteristics which underlie empirical assessment methods. The utility of fines content (proportion finer than 74 microns) as an index to liquefaction susceptibility is the prime example. The potential limitation of such empirical criteria is that the link between the index and the behaviour may not manifest in the same way in different geological settings. Zhu & Law (1988) among others have noted that the Seed et al (1983) fines corrections were developed from alluvial soils containing clay minerals. Boulanger & Idriss (2006, 2007) show that these fines corrections do not apply equally well to silty sands, sandy silts and silts (termed transitional soils) that do not have plastic fines. The significance of plasticity (colloidal activity) was first recognised in China as reflected in the 'Chinese Criteria'. Chang (1987), indicates that the peneplain and subdued coastal regions of China produce sands containing more silt and clay than are present in the predominantly uniform sands emanating from the more rugged geomorphology of Japan. Kramer (1996) notes that well graded natural sands are generally less susceptible to liquefaction than uniformly graded sands, and this is reflected in the overwhelming representation of uniformly graded sands in the liquefaction database. Clearly, natural soils having the same fines content can have quite different colloidal fractions which impart characteristics that impede grain movement and liquefaction.

Consideration of the geological setting was urged by Pyke (2003) in commenting on the NCEER criteria. Pyke noted that the NCEER procedures are formulated from experience of soils that have liquefied in earthquake events. Pyke emphasised that these soils are consistently young, uniformly graded clean sands and questioned the relevance of the NCEER recommendations to other soil types. The susceptibility of sediments ranges from very high for post-Pleistocene river channel and delta deposits formed in the last few hundred years to very low for all pre-Pleistocene soils. In the textbook 'Geotechnical Earthquake Engineering', Kramer (1996) concludes the review of liquefaction assessment by stating:

'Liquefaction susceptibility can be judged on the basis of historical, geologic, compositional, and state considerations. Geologic, compositional and state criteria must be met for the soil to be susceptible to liquefaction; if any of these criteria are not met, the soil is nonsusceptible to liquefaction.'

This would seem to provide a more widely informed and reasonable initial screening method for liquefaction potential than the common practice of automatically invoking the NCEER procedures.

4.4 Fabric

The significant effect of fabric is well illustrated by the difference in liquefaction resistance of laboratory specimens at the same relative density when undisturbed and reconstituted or when reconstituted using different methods. Fabric is a controlling factor in uniformly graded sands, and its potential to affect liquefaction resistance increases with the addition of finer particles. The arrangement of particle contacts is a response to depositional factors and the subsequent stress regime as contacts adjust to carry load. Resistance to liquefaction is governed by the frequency of particle contacts and their robustness in response to the cyclic rotation of principal stresses. Santamarina (2001) and Mitchell & Soga (2005) provide comprehensive discussions of fabric from the geotechnical engineering perspective.

Jeffries & Been (2006) note that fabric is of equal importance to density and confining stress (i.e. state) in liquefaction resistance. While fabric has a critical influence it is also the most difficult property to assess and quantify in a manner that is feasible in engineering practice. Research on this daunting problem is ongoing but, considering the vast literature on liquefaction currently being produced, it can be argued that a greater focus on fabric would be appropriate. A more robust fabric stiffens the soil structure and increases its resistance to cyclic load. The small strain stiffness as measured by shear wave velocity would seem to hold promise as at least an indicator of liquefaction resistance (Roy, 2008). Additionally, the effect of fabric is intrinsically captured in liquefaction assessment by considering induced strain rather than shear stress as argued by the proponents of cyclic strain theory (Schneider & Moss, 2011, Dobry, 2012). Development of liquefaction is a medium to large strain process which is justification for relating it to large strain penetration resistance. However, the process cannot initiate without first overcoming the soil structure at small strain.

Mechanical changes to fabric occur over time and, in the absence of chemical effects, are the reason liquefaction resistance increases with the age of the soil. The mechanical adjustment of particle contacts with time can be seen in SEM images that show the way stress cracking modifies the particle shape (Michalowski & Nadukuru, 2012). The resulting change in granular soil properties with time is well recognised in general geotechnical practice as increased stiffness and strength (Dramola, 1980; Mesri et al , 1990; Schmertmann, 1991; Mitchell & Soga, 2005). If the changes that occur over time are accepted in general there is good reason to also consider these in liquefaction assessment.

3. AGE EFFECTS

Seed (1979) tested undisturbed and reconstituted specimens of sands with known ages up to 10^6 days (≈ 3000 years) and found the liquefaction resistance increased by up to 75%.

Ishihara et al (1978) reported on broadly similar testing on alluvial silty sands and sandy silts from three locations near Tokyo. They showed that modest overconsolidation ($1 \leq OCR \leq 2$) increased cyclic resistance and that this effect became more pronounced as the fines content increased. The increase in resistance from OCR = 1 to 2 was 40% for zero fines and 70% for 100% fines. In Vancouver, Campanella & Lim (1981) tested natural sandy and clayey silts and also found liquefaction resistance increased markedly with aging and overconsolidation. Kokusho et al (2012) report on testing with a triaxial apparatus that incorporated a miniature cone to investigate more directly how cyclic load resistance varies with cone resistance. Specimens were lightly cemented with the purpose of simulating geological aging. They found that the effect of fines content in increasing liquefaction resistance at the same cone resistance increased with the degree of their simulated aging effect. That is, the liquefaction resistance of young soils was not as affected (improved) by a fines content as aged soils, both having the same penetration resistance.

In the 1964 Niigata earthquake in Japan which initiated the current liquefaction assessment method, the soils that liquefied were alluvial sands and hydraulic fills placed after the late 19th century. Much older deposits did not liquefy (Terzaghi et al, 1996). In the 1976 Tangshan, PRC earthquakes, the effects of liquefaction were observed in a 20,000 km^2 area around the Ruan river southeast of Tangshan City. The most pervasive liquefaction occurred in the young alluvial deposits and became progressively less towards the older deltaic soils (Koester, 1999).

The case records used to develop the NCEER shear wave velocity based liquefaction criteria (Andrus & Stokoe, 2000) were for sands less than 3,000 years old. Subsequent studies have expanded the database and included case histories for sands up to several million years old (Hayati & Andrus, 2009). The results indicate that the liquefaction resistance increases at just over 10% per log cycle of time.

Lewis et al (1999) report the results of detailed investigations of over 60 sites on the Charleston peninsula, South Carolina where liquefaction resulted from a large earthquake in 1886. There was abundant relict evidence around Charleston of the extent of liquefaction in clean sands originating as beach features, and also evidence of a lack of liquefaction in similar but older sands. Data from 33 sites ranging in age from 85,000 to over 200,000 years indicated liquefaction resistances on average 1.5 to 2.5 times greater than obtained using the UC Berkeley CSR-N boundary curve (Seed et al, 1983) which essentially is the current NCEER recommendation.

Motivation and support for the substantial effort on the Charleston peninsula arose from the presence of nuclear reprocessing facilities on the South Carolina Coastal Plain (SCCP) at Savannah River, Georgia. Arango et al (2000) describe studies undertaken to assess the need for foundation retrofitting of nuclear reprocessing facilities at the Savannah River Project. These facilities were supported by silty and clayey sands (fines content ≈ 10-20%) of Miocene age below the water table having SPT N-values varying between 3 and 15 with numerous values being below 5. Assessment based on the Seed et al (1983) chart indicated a liquefaction resistance approximately one-half the design CSR. Concerns raised by the Regulatory Agency lead to careful sampling with efforts to ensure quality described as "enforced to the extreme". Cyclic load testing at UC Berkeley indicated liquefaction resistance values 10% to 100% greater than the design CSR. Arango et al (loc. cit.) combined these results with the Seed (1979) and the Lewis et al (1999) information described above, plus performance data of a one million year old sand deposit in the 1994 Northridge earthquake, to define a relationship between liquefaction strength gain and time. This is shown as the upper curve on Figure 2. They report that the Regulatory Board permitted the ongoing operation of the nuclear reprocessing facilities without foundation upgrading.

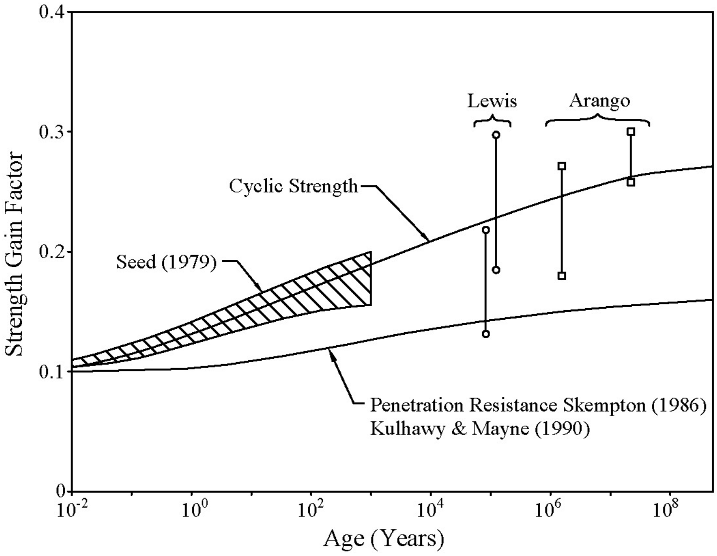

Figure 2: Cyclic strength and penetration resistance of aged sand deposits (after Arango et al, 2000)

The lower curve on Figure 2 shows the effect of the deposit age on penetration resistance based on recommendations of Skempton (1986) and Kulhawy & Mayne (1990). The effect of age on penetration resistance is less than its effect on liquefaction resistance. Jamiolkowski et al (1985) reported that their test data showed the beneficial effect of mechanical overconsolidation and prestraining on liquefaction resistance to be about three times the corresponding effect on penetration resistance.

Leon et al (2006) incorporated both curves on Figure 2 into a procedure for assessing the effect of deposit age on the liquefaction resistance deduced from penetration resistance. They report investigations of different palaeo-liquefaction sites on the SCCP which support this age correction to the Seed/NCEER liquefaction resistance criteria for Holocene sands.

Moss et al (2008) tested undisturbed and reconstituted specimens of a late Pliocene sand in California in a similar manner to the original work of Seed (1979). The estimated age of the sand deposit, 2.5M years, had been established by detailed geological mapping in 1994 as indicated in Moss et al (loc. cit.). The liquefaction resistance increase factor was 2.2 which is compatible with the findings of the Lewis/Arango investigations described above. Moss et al indicated that a programme of similar investigations at other sites of known age is being undertaken.

Ongoing research on the effect of sand age is being performed at field test sites (Geiger et al, 2010; Saftner, 2011). The work includes induced field liquefaction as part of the US National Science Foundation programme ‘Network for Earthquake Engineering Simulation’ (Saftner, loc.cit.).

4. APPLICATION OF EMPIRICAL CRITERIA

One aspect of liquefaction assessment that needs to be better understood in practice is the use of averaging verses point-by-point characterisation of the soil resistance profile. Inspection of the current liquefaction database (Moss, 2003) shows that the case record soil profiles are characterised by the *average* resistance of the zone judged to be most critical. Figure 3 is an example of the interpreted average resistance value for the assumed liquefied zone that is in the database. There is significant variation from the average value in the critical zone. It is necessary that the same approach is adopted in applying the resulting liquefaction criteria. Specifically, applying the criteria to a site on a point-by-point basis is inappropriate as it introduces significant conservatism. Unfortunately this practice is encouraged by the ease of automated spread sheet analysis of continuous CPT records.

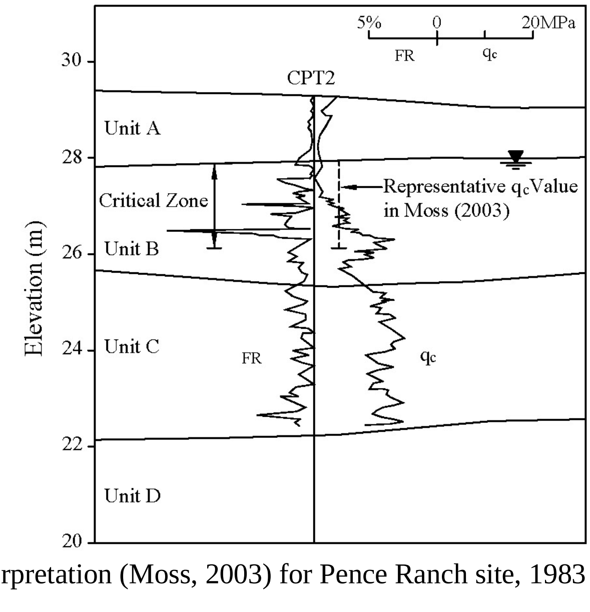

Figure 3: CPT interpretation (Moss, 2003) for Pence Ranch site, 1983 Borah Peak earthquake case record

5. CONCLUDING COMMENTS

Clearly Australia has coastal Holocene deposits that fit the NCEER prescription. Australia also has much older sediments and residual soils that are not represented in the databases from which the empirical procedures derive. The reliability of liquefaction assessment would be significantly improved if suitably informed engineering geologists, considering the advice of Youd & Perkins (1978) and Kramer (1996), were involved in screening for liquefaction susceptibility. If a site fails to pass this initial screening, then the subsequent engineering calculations should consider the effect of deposit age on penetration resistance and liquefaction resistance illustrated by Figure 2. These measures are among the most beneficial changes to geotechnical liquefaction assessment practice that could be implemented relatively quickly. Space restrictions do not permit discussion of another important aspect which is the type of earthquake ground motions in Australia compared with the NCEER database, and the validity for Australia of the “Simplified Method” of characterising the earthquake demand based on cyclic stress ratio. See for example Kayen & Mitchell (1997) and Liyanapathirana & Poulos (2001).

In the longer term, the best prospect for improvement is probably to move away from relying solely on empirical criteria towards a mechanics based approach underpinned by a theoretical framework. The critical state approach of Jefferies & Been (2006) provides important insights that can explain apparent anomalies in empirical data and enable this hard won information to be interpreted with greater reliability.

This paper has attempted to highlight some limitations of current liquefaction science and practice, and deficiencies in the NCEER recommendations. The economic penalty of inappropriate application of empirical liquefaction criteria is considerable and this is being experienced by projects today. In the United States, O’Rourke (2011) has called for a new workshop process to address the conflicts in liquefaction assessment. In the meantime, responsibility for improper and overly conservative liquefaction assessment will primarily reside with those who use the empirical NCEER criteria in conditions for which they are not applicable.

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