Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)

Integrated approach to liquefaction hazard assessment

Approche intégrée de l'évaluation des risques de liquéfaction

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ABSTRACT: Assessment of liquefaction potential in literature is described based on single strategy approaches. Little effort has been dedicated to study how and why in some cases different criteria can and should be combined. This study begins by classifying and listing some of the most widely used single strategy approaches for liquefaction hazard assessment outlining their limitations and strengths. Situations where a single strategy approach may not be sufficient to completely characterize liquefaction potential at a site are identified and the requirements that an integrated approach should fulfill are described. Based on these requirements, available single strategy approaches are selected and combined into an integrated approach. The application of a so formulated integrated approach and its advantages over a single strategy approach are shown for one case study of a soil profile offshore Taiwan. For the considered case study, standard single strategy approaches are considered less reliable as these have not been developed for and/or sufficiently validated against similar conditions where the liquefaction depth may exceed 20 m, for which liquefaction may occur in the fine-grained soils and for which standard empirical CPT based correlations do not correctly account for effect of fines.

RÉSUMÉ : L'estimation du potentiel de liquéfaction dans la littérature est décrite sur la base d'approches à stratégie unique. Peu d'efforts ont été consacrés à l'étude de comment et pourquoi différents critères peuvent être combinés. Cette étude commence par classer et énumérer certaines les approches à stratégie unique les plus utilisés, en soulignant leurs limites et points forts. Les situations dans lesquelles une approche à stratégique unique donnée peuvent ne pas être suffisantes et les exigences qu'une approche intégrée doit satisfaire sont identifiées. Sur la base de ces exigences, les approches à stratégie unique sont sélectionnées et combinées en une approche intégrée. L'application d'une approche intégrée ainsi formulée et ses avantages par rapport à une approche à stratégie unique sont présentés pour une étude de cas d'un profil de sol offshore dans le détroit de Taiwan. Pour le cas considéré, les approches standard à stratégie unique sont considérées moins fiables car elles n'ont pas été développées pour et/ou suffisamment validées par rapport à des conditions similaires où la profondeur de liquéfaction peut dépasser 20 m, où la liquéfaction peut se produire dans les sols à grains fins et où les corrélations empiriques standard basées sur le CPT ne prennent pas correctement en compte l'effet des particules fines.

KEYWORDS: soil liquefaction, fines content, integrated approach.

1 INTRODUCTION.

Seismic soil liquefaction is one of main causes of earthquake induced damages with some notable and widely recognized case histories, one of the earliest ones dating back to 1918 with the failure of the Calaveras Dam (Hazen, 1920) in California. The year in which early case histories probably brought liquefaction to the serious attention of engineers was 1964 when the Niigata earthquake in Japan and the Anchorage earthquake in Alaska occurred both causing serious liquefaction and damage. Since then, studies on mechanism, prediction and remedial measures were commenced and are still among the most researched topics in geotechnical earthquake engineering. Approaches to liquefaction assessment can academically be classified in historical, geologic, compositional, state criteria (Kramer, 1996) and empirical correlation with in situ test results and may greatly vary with respect to the scale considered and the level of detail. For the purpose of detailed engineering assessment, the state criteria, assessed by means of laboratory tests and the empirical correlations with in situ tests results, are most frequent because of the possibility to achieve a quantitative estimate of liquefaction susceptibility. Therefore, this paper focuses on these two specific types of approaches. Both these approaches express the liquefaction potential in the form of a Factor of Safety (see Eq. 1) directly proportional to the Cyclic Resistance Ratio (CRR) and inversely proportional to the Cyclic Stress Ratio (CSR).

$$FoS = CRR/CSR \tag{1}$$

Throughout this study it will be assumed the case of CSR determined by mean local site response analysis; in principle this is also the most accurate and suggested method unless in situ acceleration measurements are available.

While in technical literature studies focus on single strategy approaches to evaluate CRR, the present paper tries to identify some of the main limitations and benefits of the mostly used, stress based, single strategy approaches and then identifies potential cases when an integrated approach is needed. The features that an integrated approach should have are identified and an example of such an approach is described for a given case history.

2 FEATURES OF MOST COMMON SINGLE STRATEGY APPROACHES.

2.1 *Liquefaction assessment by means of laboratory tests*

The most common laboratory tests for characterization of liquefaction potential assessment of a site, are the cyclic triaxial test (either axisymmetric or true triaxial test), direct simple shear tests and torsional shear tests. Strictly speaking the state of soil in the context of liquefaction hazard assessment of coarse-grained soils is generally referred to as the relative density and in situ stress conditions. However, experience obtained in the last 40 years shows that beside the state of soil several other aspects come into play in stress-based measures of CRR of saturated soils (e.g. di Prisco & Muir Wood, 2012). These main aspects, the ways they are accounted for in cyclic tests, and some relevant references where the reader can find more details are summarized in Table 1.

Table 1. Main factors, other than state of soil, that influence cyclic stress-based measures of liquefaction resistance and corresponding example references.

Description	Sample or Test Parameter	Example tests references
Soil fabric and depositional history of the soil in situ	Sample preparation	Ladd 1974; Porcino et al., 2004
Previous earthquakes/load history	Small amplitude cyclic preloading	Seed et al., 1977; Oda et. Al, 2001
Soil aging effects	Consolidation time	Seed, 1979; Tatsuoka et. al, 1988
Soil granulometric composition	Parameters related to shape of particle size distribution including e.g. fines content and clay content	Lee and Fitton, 1969; Seed and Idriss, 1971; Vaid et al. 1990, Chien et al., 2002
Sample disturbance	Techniques related to soil samples	Mulilis et al. 1975; Porcino et al., 2004
Tests boundary conditions	Including regularity and multidimensionality of loading and membrane penetration effect	Ishihara and Nagase, 1988; Nicholson et al.1993

2.2 *Liquefaction assessment by empirical correlations with in situ tests data*

For evaluation of liquefaction resistance based on standard penetration test (SPT), the NCEER 2001 (Youd et al., 2001) proposes liquefaction base curves (and correspondent equations) as function of fines content (Seed et al, 1985), separating data indicative of liquefaction from data indicative of non-liquefaction in terms of calculated CSR and corrected normalized (to 100 kPa) SPT blow count $(N_1)_{60}$ valid for M=7.5.

For evaluation of liquefaction resistance based on cone penetration test (CPT), the NCEER 2001 (Youd et al., 2001) proposes a liquefaction base curve (and correspondent equations) valid for fines content up to 5% (Robertson & Wride, 1998), separating data indicative of liquefaction from data indicative of non-liquefaction in terms of calculated CSR and corrected normalized (to 100 kPa) CPT blow count q_{c1n} valid for M=7.5. It should be noted that use of boreholes for soil type verification is strongly recommended when CPT based criteria are used.

Boulanger and Idriss, (2014, 2016) include some notable changes from the original NCEER 2001 methods. The stress exponent in the overburden correction factor requires an iteration effort, the magnitude scaling factors and the clean sand equivalent correction method are updated, and a probabilistic term in the reference (magnitude M=7.5 and $\sigma_v' = 1atm$) CRR is included.

The Japan Road Association (JRA, 1996) is more often used in Asia than in other regions. In this case the FoS is formulated as a function of the cyclic triaxial dynamic shear strength ratio (R) instead of CRR and the seismic shear stress ratio (L) instead of CSR hence, compared to Eq. 1, a factor approximately in between 0.7 and 0.65 applies to both terms.

Cetin, et al., (2004) developed updated correlations for assessment of the likelihood of initiation (or “triggering”) of soil liquefaction based on SPT. These new correlations eliminate several sources of bias intrinsic to previous, similar correlations, and they provide greatly reduced overall uncertainty and variance.

Stark and Olson (2005) based on the results of 180 field case histories, developed normalized CPT based liquefaction/non liquefaction boundaries, for M=7.5 in sandy soils as a function of fine content.

It should be noted that correlations with shear wave data velocities are not mentioned above because they are used less often than correlations with SPT and CPT data (Siegel, 2013).

Finally, it should also be noted that the applicability of any liquefaction assessment criteria based on empirical correlations is strictly dependent on the amount and type (plastic or on plastic) fines.

2.3 *Limitations of single strategy approaches and advantages of integrated approach*

The most notable challenges to assessment of liquefaction potential by mean of cyclic laboratory tests are related to the sample disturbance for coarse-grained soils.

It should be noted that sample disturbance and membrane penetration effect are limitations of the laboratory tests only and, in the context of liquefaction potential assessment, are more relevant aspects for coarse-grained soils and smaller samples/larger mean grain size, respectively. For silts and fine sands, for example (Seed et al., 1989) membrane penetration effect may be negligible.

Secondly the cyclic stress measure of liquefaction triggering assessment also requires turning a time-variant earthquake signal into an equivalent cyclic shear stress and an equivalent number of uniform cycles at different soil depths. Additionally, if the geotechnical conditions across the site is complex and detection of relatively thin liquefying layers is required to large depths, relying only on cyclic laboratory tests can cost significant time and resources and at times become not feasible. The above challenges may be avoided when using empirical correlations with in situ data and preferably with continuous CPT data.

Field observations used in the validation of empirical methods are based on surface manifestation of soil liquefaction and for this reason these methods are not suitable when liquefaction depth exceeds or is close to 20 m below ground level.

Another limitation of empirical methods compared to direct measure by means of cyclic laboratory tests is that they do not offer the same level of insight and confidence in the assessment of cyclic softening for silts and clays and their use is advised only in low-risk projects or in early design phases (Boulanger & Idriss, 2007; Robertson, 2009). Youd et al (2001) emphasized that the CRR based solely on fines content should be used with engineering judgement and caution.

The above challenges may be mitigated by direct measurement of CRR by means of cyclic laboratory tests.

Although due to its good repeatability and reliability CPT have been an essential part of offshore site investigations for the last 40 years, the need to improve the interpretation of CPT data in highly silty and/or compressible sands is a recognized fact and, among others, the need of carrying out more calibration chamber tests on a wider range of tests has been pointed out (Lunne, 2012).

In regions like Taiwan only recently CPT has become the most used in situ test for development of offshore wind farms and the applicability of CPT for liquefaction potential evaluation at sites offshore and its comparison with SPT based correlations (JRA method) mentioned by the Taiwanese Seismic Design Specifications and Commentary of Buildings Code and laboratory tests is a topic that is gaining attention (Kuo et al., 2021).

From the observations above is clear that all single strategy approaches are affected by some limitations. From the observations above it is also clear that an integrated approach where the state criteria are assessed by means of laboratory tests, empirical correlations with one or more situ tests results and with existing laboratory tests results from similar soils has the advantage of mitigating the above mentioned limitations that affect the single strategy approaches. An integrated approach implies extra effort and cost compared to a single strategy approach it is therefore of interest to define more in detail the conditions under which an integrated approach is advocated.

3 FORMULATION OF AN INTEGRATED APPROACH.

From the discussion above it is possible to try to summarize in the flow chart included in Figure 1, the conditions under which a single strategy or an integrated approach are required.

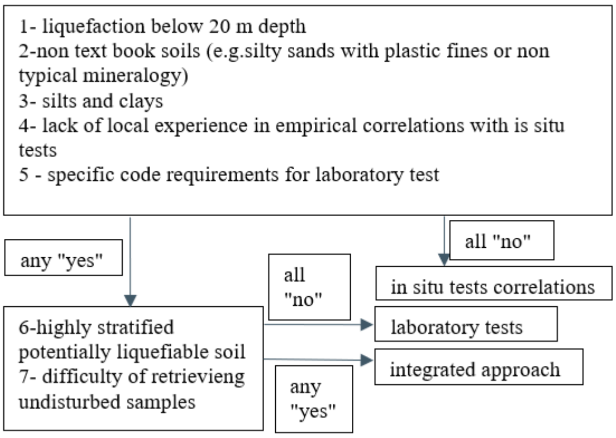

Figure 1. Flow chart describing the circumstances under which an integrated or a single strategy approach may be preferred.

Seven key questions can be indicatively considered. If the answer to the first five (Figure 1) is no then in situ test correlations can be used alone. If the answer to both question six and seven is no (Figure 1), laboratory tests can be used alone. If the answer to any of the first five questions is yes and the answer to any of the following two questions is yes (Figure 1) then an integrated approach is advised.

As example of silty sands with unusual mineral content and silts, the Central Western Taiwanese alluvial deposits studied by Huang and coworkers can be mentioned. Their study of Mai Liao Sand (Huang et al., 1999) shows a significantly more compressible sand than typical clean quartz sand reported in literature and do not support the idea of fines content adjustment in its conventional sense (Huang et al. 2006).

For the case of silts and clays for which in situ test correlations have limited applicability (e.g. Boulanger & Idriss, 2007; Robertson, 2009) a screening phase based on simple classification tests followed by cyclic laboratory tests maybe sufficient (Sancho et al, 2006) except for the case of highly stratified potentially liquefied soil for which a correlation with continuous CPT maybe necessary.

The concept of integrated approach discussed here therefore suggests that, under the circumstances described in Figure 1, the standard definitions of liquefaction domains as a function of in situ test data (e.g. Stark and Olson, 1995; Robertson and Wride, 1998) is considered as a reference case, but in addition consistency between these domains and the cyclic laboratory test results on in situ soils must be shown. Doing so, if necessary, the domains as per standard criteria (see section 2.2) may be adjusted to correctly account for effect of fines contents/mineralogy. One innovative aspect of what is proposed here is the adjustment of previously defined liquefaction domains (defined in the q_{c1n}-CRR or in the $(N_1)_{60}$-CRR plane) to fit site specific laboratory tests data. Additionally, it is proposed that in a similar way as done for silty sands, similar domains can be considered for other potentially liquefying soil such as sandy or clayey silts.

Finally, it should be underlined that in the integrated approach described here data from in situ and laboratory tests from similar soil available in literature are also included.

4 EXAMPLE OF APPLICATION OF AN INTEGRATED APPROACH.

An example case study for an offshore site west of Taiwan, Changhua County is considered. Soil conditions are highly layered and consisting of loose to medium dense silty sand, silt and soft silty clay with low to intermediate plasticity. Due to significant river discharge these alluvial facies are found to large depths, exceeding 30 m. Huang and his co-workers have done extensive work on assessing the mechanical properties and the liquefaction potential for alluvial deposits of silty sands present in this area of Central Western Taiwan (MLS- Mai Liao Sand and YLS -Yuan Lin Sand, Changhua County) having comparable values of fines and minerals content. Following the Chi-Chi earthquake, Huang et al., (2003) back analyses of sand liquefaction potential with significant amount of fines have found that existing empirical correlations with in situ tests can lead to significantly different results. This is due to the nature of the sediments, the relatively soft and crushable nature of YLS and MLS and the effects of fines on penetration resistance deriving from the significant amount of muscovite and chlorite in addition to quartz. In a subsequent study (Huang, 2006) the effect of fines content on cone tip resistance of MLS is accounted for by means of regression analysis of CPT calibration chamber tests. The form of the empirical equation (Fioravante et al. 1991) of normalized cone tip resistance q_{c1n} (see Eq. 2) allows to evaluate the fines content effect by mean of regression coefficient (C1 and C2) that are function of the fines content circumventing the above-mentioned problem.

$$q_{c1n} = \left(\frac{q_c}{p_a}\right) \cdot \left(\frac{p_a}{\sigma'_v}\right)^{C_1+C_2} \quad (2)$$

For the chosen empirical correlations (Stark and Olson, 1995) the liquefaction domains on a $q_{c1n} - CRR$ plot, can then be identified for each of the soil units. Considering q_{c1n} allows to properly account for effect of fines on the normalized cone tip resistance. Following the procedure described in section 3 cyclic laboratory test results and undisturbed cyclic laboratory test results from literature (Huang et al., 2006) are included. Cyclic direct simple shear test results, reference undisturbed cyclic triaxial test results (Huang, 2006) together with the resulting liquefaction domains for this example are shown in Figure 2. Undisturbed samples (Huang, 2006) are sampled using the Laval large diameter sampler and are freezed above ground. It is noted that due to sample disturbance in cyclic direct simple shear tests on silty sands with mean fines content of 15% (yellow dots in Figure 2), the CRR would largely be underestimated if results from undisturbed cyclic triaxial tests (Huang, 2006) on MLS silty sand were not considered or if the Stark & Olson (1995) domain was adopted. Both observations are in agreements with the findings from Huang et al. (2006) Liquefaction boundary for sandy silts (mean fine content 65%) coincide with the one of Stark and Olson (1995) for silty sand with fines content of 35%. Similarly, a liquefaction boundary is obtained for clayey silts. For the last two soil units, effect of sample disturbance is less prominent and correction for sample disturbance is not considered. It should be noted that CPT tests do not allow for direct determination of fines content so fines content can be determined from nearby boreholes, while for undisturbed laboratory samples fines content is measured from adjacent samples. All liquefaction boundaries are obtained for tests and cyclic stress ratios not exceeding 0.35 because larger values of CSR are not practically relevant.

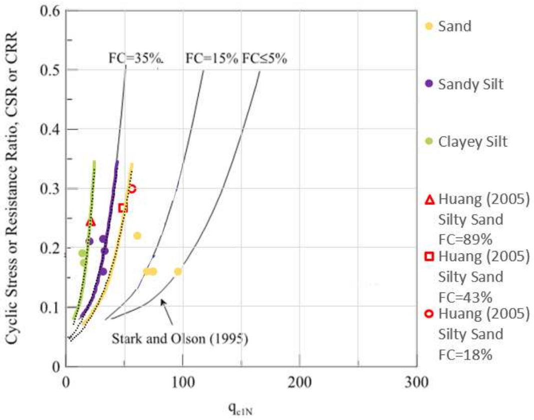

Figure 2. Plots of liquefaction domains for different soil units in terms of normalized cone tip resistance (Huang et al, 2006) and cyclic resistance ratio, obtained by integrated approach. Cyclic laboratory tests results (yellow, purple and green dots), reference undisturbed test results (red dots) and Stark & Olson (1995) empirical criterion curves are shown for reference/comparison.

5 CONCLUSIONS.

The purpose of the present study is to briefly review the most commonly used methods for liquefaction triggering assessment with the aim of highlighting their strength and limitations and with these in mind to identify specific circumstances when the practicing engineer needs to use laboratory and in situ tests in a complementary way using an integrated approach.

Based on these considerations the integrated approach is described with reference to cyclic stress driven laboratory tests, empirical correlations with in situ test results and including also applicable test data in literature when available.

As one of the possible outcomes, it is suggested that in case of sandy soils with non-standard mineralogy, sand with plastic fines, silts/clayey silts, or in case of highly stratified soils and/or liquefaction potential below 20 m depth, standard correlation between CRR domain and normalized CPT/SPT should be verified and, if necessary, could be modified by comparison with results from cyclic laboratory tests and applicable results from literature when available.

A practical example of integrated approach for a case of alluvial deposits offshore Taiwan is described. Liquefaction boundaries are obtained by considering a modified Stark and Olson (1995) empirical criterion considering the normalized cone tip resistance obtained by Huang et al (2006). Modified boundaries are obtained considering also cyclic direct simple shear tests results on clayey silts, sandy silts and silty sands and results from cyclic triaxial tests on undisturbed MLS samples from literature.

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