Transactions, SMiRT-24
BEXCO, Busan, Korea - August 20-25, 2017
Division VI

A REVIEW OF STATE OF ART FOR SPT BASED LIQUEFACTION HAZARD ASSESSMENT

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ABSTRACT

Assessment of soil liquefaction potential to preclude associated ground failure is important for ensuring safety of NPP foundations. Among different types of in-situ test based methods for assessment of liquefaction potential, standard penetration test (SPT) based empirical method is well established and hence a preferred choice. USNRC (2003) provides guidance for Liquefaction Hazard Assessment (LHA) by empirical method, primarily based on studies by Youd et al. (2001). This work utilizes the database of earthquake induced liquefaction for earthquakes up to year 1981.

Subsequent to year 1981, several major earthquakes, e.g. M-6.9 Kobe earthquake of 1995, M-7.5 Kocaeli earthquake of 1999, M-7.6 Chi-Chi earthquake of 1999, 2010-11 Canterbury earthquake sequence and M-9.0 Tohoku earthquake, had induced liquefaction.

Using updated database of liquefaction histories, method by Youd et al. (2001) was modified/ updated by several researchers viz. Cetin et al. (2004), Idriss & Boulanger (2004), Idriss & Boulanger (2008), and Idriss & Boulanger (2014). However, differences exist with respect to prediction of liquefaction hazard while following these recent methods.

The paper evaluates comparative performance of SPT based methods suggested by different researchers, using the liquefaction case history database as basis. The methods included for evaluation are Youd et al. (2001), USNRC (2003) and Idriss & Boulanger (2014). The performance is evaluated by comparing with actual observation (liquefaction or no-liquefaction) at various sites and identification of number of false negatives (i.e. any method predicting a liquefied site as non-liquefied). The criterion based on false negatives is applied for performance evaluation keeping in view that liquefaction potential needs to be practically eliminated at NPP sites.

This study revealed the limitations/ uncertainties in all the considered empirical methods with respect to prediction of liquefied sites, as all methods predicted some false negatives. The work also brings out areas where improvement can be made while developing regulatory acceptance criteria for liquefaction hazard assessment.

INTRODUCTION

Assessment of soil liquefaction potential to preclude associated ground failure is important for safety of NPP foundations. Among different types of in-situ test based methods for assessment of liquefaction potential, standard penetration test (SPT) based empirical method is well established and hence a preferred choice. In this method liquefaction resistance of a soil stratum is represented in terms of Cyclic Resistance Ratio (CRR) and earthquake induced stress as Cyclic Stress Ratio (CSR). Factor of safety against liquefaction is evaluated as ratio of CRR to CSR.

Pioneering work in the field of SPT based Liquefaction Hazard Assessment (LHA) was undertaken by Seed and Idriss (1971), wherein a simplified method for evaluation of liquefaction potential based on SPT results was presented. Subsequently, this method was modified and improved by several researchers [Seed et al. (1984); Youd et al. (2001), Cetin et al. (2004), Idriss and Boulanger (2004), Idriss and Boulanger (2008), and Idriss and Boulanger (2014)].These researchers either proposed different formulations for evaluating the parameters for estimating factor of safety against liquefaction or used an updated/corrected liquefaction database.

Seed et al. (1984) used 126 case histories for liquefied and non-liquefied soil sites for earthquakes recorded up to year 1981. Dependence of CRR or liquefaction resistance on presence of fines was addressed for the first time in this work. Youd et al. (2001) used the same database as that of Seed et al. (1984) with minor modification in the curve for estimation of CRR for very low SPT-N values. Formulations for estimation of different parameters used in liquefaction hazard assessment were provided based on consensus decision during a workshop organized by the National Center for Earthquake Engineering Research (NCEER) in the year 1996 [Youd and Noble, 1997]. These revised formulations took account of the developments in the field subsequent to Seed et al. (1984).

From a nuclear regulatory perspective, USNRC RG 1.198(2003) [USNRC, 2003] provides guidance for liquefaction hazard assessment by empirical method. However, this RG is primarily based on studies by Youd et al. (2001) which utilizes past earthquake induced liquefaction database up to year 1981. Subsequent to year 1981, several major earthquakes have induced liquefaction. These include, M-6.9 Kobe earthquake of 1995, M-7.5 Kocaeli earthquake of 1999, M-7.6 Chi-Chi earthquake of 1999, 2010-11 Canterbury earthquake sequence, and M-9.0 Tohoku earthquake. Moreover, recent seismic events in the site regions of Kashiwazaki Kariwa and Fukushima NPPs in Japan, and North Anna NPP in USA have also pointed to the possible exceedance of design basis ground motion.

Cetin et al. (2004) used an updated database, with 201 field case histories for earthquakes up to the year 1995, for derivation of liquefaction triggering curve. Out of 201, 44 case histories were taken from Kobe earthquake of 1995. Cetin et al. (2001) also provided modified formulations for estimation of different parameters.

Idriss and Boulanger (I&B) (2004), and I&B (2008) improved the database further with total of 230 case histories. Citing inconsistency in classification of 21 cases of Kobe earthquake of 1995 used by Cetin et al. (2004), the database was modified after verification with the original references. Database of I&B (2004) and I&B (2008) contained liquefaction case histories up to year 1995. This work was further updated in 2014 [I&B (2014)] by adding 24 case histories from 1999 Kocaeli and Chi-Chi earthquakes. Two non-liquefied cases from previous database (I&B (2008)) were removed due to insufficient details. Total case histories thus became 252 in I&B (2014).

In summary, Seed et al. (1984) method was widely used till the year 2001. Youd et al. (2001) brought out modifications in this method based on state of art at that point of time. USNRC (2003) while developing regulatory acceptance criteria, adopted Youd et al. (2001) method with minor modifications. The work of Cetin et al. (2004) was a major revision in database albeit overshadowed by inconsistencies in the database. I&B (2004, 2008) used corrected and updated database over that of Cetin et al. (2004). The latest work of I&B (2014) improves upon the work of 2008, and thus supersedes the previous work.

Based on the review of developments in SPT based LHA, three candidate methods viz. USNRC (2003), Youd et al. (2001) and I&B (2014) were selected for further assessment. The above methods used different databases to generate empirical formulations for liquefaction hazard assessment. Current study is intended to use a comprehensive database along with the formulations of these three methods. The results of this assessment are then compared with actual site occurrence (liquefied/ not liquefied) to evaluate prediction capability of these methods. In general, a false positive (method suggests possible liquefaction but actually site did not liquefy) is considered as a safe situation compared to a false negative (site actually liquefied but evaluation shows no liquefaction potential) for an NPP site. There are uncertainties in various parameters and empirical relations used in empirical methods of LHA. This became evident during the current work when empirical methods predicted liquefied sites as non-liquefied in few cases.

PARAMETERS FOR LIQUEFACTION HAZARD ASSESSMENT

Estimation of CSR

Cyclic stress ratio depends on earthquake characteristics and depth of soil layer from existing ground level. Seed and Idriss (1971) defined CSR as ratio of average shear stress to effective normal stress at any depth and formulated the following equation for calculation of the cyclic stress ratio:

$$CSR = \frac{\tau_{av}}{\sigma'_{vo}} = 0.65 * \left(\frac{a_{max}}{g}\right) * \left(\frac{\sigma_{vo}}{\sigma'_{vo}}\right) * r_d \tag{1}$$

Where, a_{max} = peak horizontal acceleration at the ground surface generated by the earthquake; g = acceleration due to gravity; σ_{vo} and σ'_{vo} are total and effective vertical overburden stresses, respectively; and r_d = stress reduction coefficient, which is an empirical function of depth below free ground surface and magnitude of earthquake.

Estimation of CRR

Cyclic Resistance Ratio (CRR) depends on strength characteristics of the soil, amount of fines (soil particles with size < 75μ) in soil, earthquake duration effects etc. Evaluation of CRR requires results of soil investigation like Standard Penetration Test (SPT), Cone Penetration Test (CPT), or Shear wave velocity (Vs) test representing the soil strength. SPT is the most common method used for evaluating soil resistance. Figure-1 shows the typical schematic of soil resistance against earthquake induced stress. A curve (known as liquefaction triggering curve) demarcating the liquefied and the non-liquefied sites is the primary basis for evaluation of CRR. In general, liquefaction triggering curves are provided for different levels of fines content (soil particles with size < 75μ) in soil. Increase in fines content increases CRR and hence liquefaction resistance. Basic expression for CRR is developed for an earthquake magnitude of 7.5 and is designated as $CRR_{7.5}$. For magnitudes other than 7.5, Magnitude Scaling Factor (MSF) is applied. To account for the nonlinear dependence of CRR on effective overburden stress, Seed (1983) introduced a correction factor K_σ to extrapolate the simplified procedure to soil layers with overburden pressures >100 kPa.

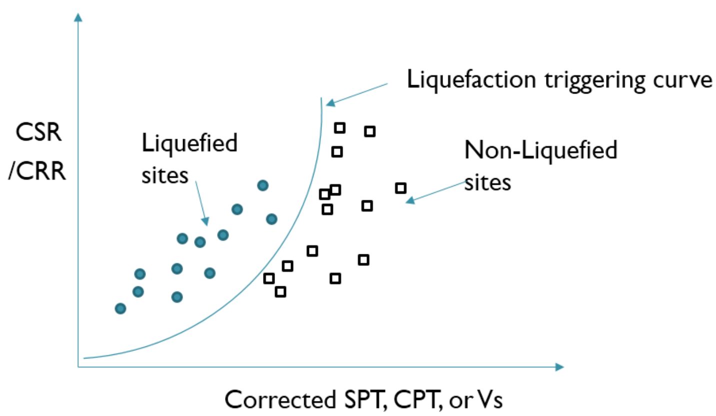

Figure-1 Typical Liquefaction triggering curve

The liquefaction resistance (CRR) of dilative soils (moderately dense to dense granular materials under low confining stress) increases with increasing static shear stress. Conversely, the liquefaction resistance of contractive soils (loose soils and moderately dense soils under high confining stress) decreases with increasing static shear stresses. To incorporate the effect of static shear stresses on liquefaction resistance, Seed (1983) introduced a correction factor K_α to be applied for sloping grounds where initial static shear stress is present. For level ground, K_α is 1.0. Hence, including all factors, CRR can be determined for a site using the following expression:

$$CRR = CRR_{7.5} * MSF * K_{\sigma} * K_{\alpha} \tag{2}$$

Estimation of Factor of safety

Factor of safety against liquefaction is determined as ratio of CRR to CSR.

$$FOS = \frac{CRR}{CSR} \tag{3}$$

ASSESSMENT OF SPT BASED EMPIRICAL METHODS

Based on the review of developments in SPT based LHA, three candidate methods viz. USNRC (2003), Youd et al. (2001) and I&B (2014) were selected for assessment. While the first two methods are similar and uses same earthquake induced liquefaction database, I&B (2014) uses an updated database and more refined procedure for LHA. Major improvements in I&B (2014) method over the other two is highlighted in following subsection.

Improvements in Idriss & Boulanger (2014) Method over USNRC (2003)

In addition to providing modified formulations considering updated database, I&B (2014) also introduced dependence of various parameters on additional soil properties which was evident from field/ laboratory observations. Dependence of stress reduction factor on magnitude of earthquake was also introduced. Summary of improvement in evaluation of different parameters is presented below.

i. Overburden correction factor, C_N, is observed to be dependent not only on overburden stress but also on relative density of the soil [USNRC, 2003]. I&B (2014) addressed this aspect by correlating C_N with corrected SPT-N value $(N_1)_{60CS}$.
ii. Stress reduction factor, r_d, depends on magnitude of earthquake which was also discussed by Youd et al. (2001). However it was not included at that point of time due to lack of evaluation. This issue was addressed by I&B (2014) through site response analysis for several hundred cases.
iii. Magnitude scaling factor, MSF depends on the characteristics of both the imposed loading and the soil response to loading [I&B (2007), Cetin and Bilge (2012), Kishida and Tsai (2014)]. MSF relationship developed by Seed et al. (1975), Idriss (1999), Youd et al. (2001) etc. were for typical properties of clean sand alone. I&B (2014), represented MSF as a function of magnitude and $(N_1)_{60CS}$ to take into account its dependence on properties of different soils. This MSF relationship is based on the examination of cyclic testing results for a broad range of soil types and densities, analyses of strong ground motion records to develop relationships for the equivalent number of loading cycles for different soil properties (including the work of Kishida and Tsai, 2014).
iv. K_{σ} Factor: based on analysis of updated case history database and laboratory test results of frozen sand samples, I&B(2014) represented K_{σ} as a function of overburden stress and soil property $((N_1)_{60CS})$.

It is noted that I&B (2014) uses liquefaction case histories from earthquakes up to year 1999. Subsequent to 1999, some major earthquakes that resulted in liquefaction are Cantbury earthquake sequence 2010-11 and Tohoku earthquake 2011. However, to the best of knowledge of Authors, these are yet to be taken into account in SPT based methods.

Case Histories Database

Database of liquefaction case histories considered for the present assessment includes 254 records of different earthquakes from year 1944 to 1999, with magnitude varying from 5.9 to 8.3. Out of total 254 records, 136 records pertain to liquefied sites and 118 pertain to non-liquefied sites. Year wise distribution of case histories in the database is shown in Figure-2.

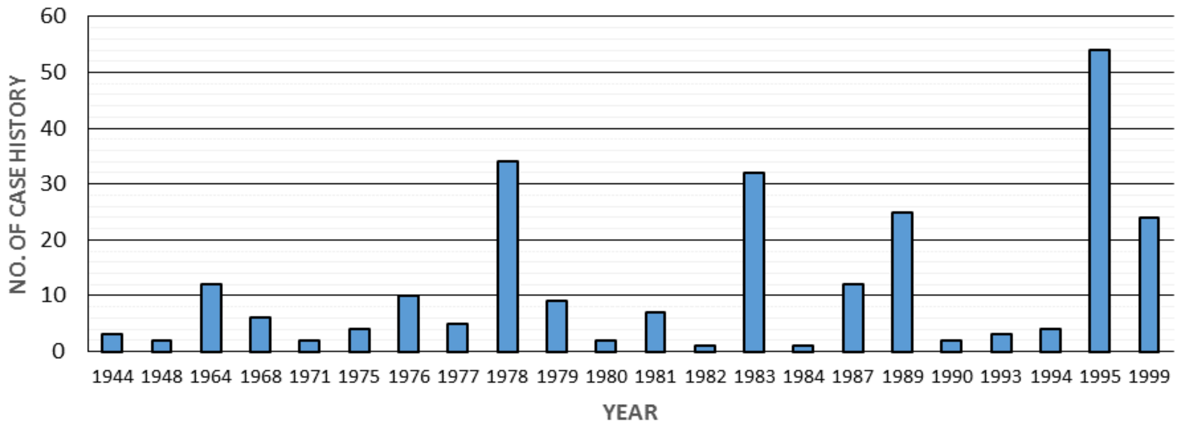

Figure-2 Year wise distribution of case histories in database

Salient observations on the Case Histories

Detailed review of the liquefaction case history database brings out the following:

i. Though it is expected that liquefaction is possible only within certain range of soil parameters and above a certain seismic level; the database indicates that the soil and ground motion parameters from liquefied sites have a wide variation. Table-1 brings out the maximum and minimum values of these parameters for liquefied sites from the case history database. It is observed that liquefaction has occurred at PGA of as low as 0.098g and in another case with fines content even above 90%.

ii. All the case histories in the database consider average depth below ground surface; i.e., if the critical zone (or zone of study) for a site is found to be extended between depths of 6 m and 10 m, the average depth would be 8 m while the maximum depth would be 10 m. Maximum average depth covered in the database for liquefied sites is 12m. This means that extrapolation of the empirical method beyond this depth will have associated uncertainties. I&B (2010) mentioned that "*the differences in the components (e.g., C_N, K_σ, r_d, MSF, $(N_1)_{60CS}$) of liquefaction analysis procedures recommended by various investigators become more important when the procedures are used to extrapolate outside the range of the case history data (e.g., depths greater than 12 m)*".

iii. General opinion has been that soil with higher fines content is not susceptible to liquefaction. Review of data from liquefied sites indicate that about 38% of the sites had fines content > 15%. Moreover, 15% of liquefied sites had fines content in excess of 35%. This brings out the importance of considering dependence of SPT value and fines content and vulnerability of strata with higher fines content.

Table-1 Minimum and maximum values of different parameters for liquefied sites in database

Parameter	Minimum	Maximum
Measured SPT (Nm)	1	20
Fines Content (FC, %)	0	92
Magnitude of Eq. (M)	5.9	8.3
Peak Ground Accl. (PGA, g)	0.09	0.84

Application of identified methods for Liquefaction Hazard Assessment

Liquefaction Hazard Assessment (LHA) in terms of Factor of Safety against liquefaction is undertaken for 254 case records mentioned in previous section using three identified assessment methods viz. USNRC (2003), Youd et al. (2001) and I&B (2014).

Factor of safety against liquefaction

Ratio of FOS calculated from Youd et al. (2001) and USNRC (2003) for different sites is presented in Figure-3. The ratio varies from 0.9 to 1.0, which indicates that, Youd et al. (2001) is generally conservative in terms of liquefaction possibility prediction than USNRC (2003) for the considered case histories.

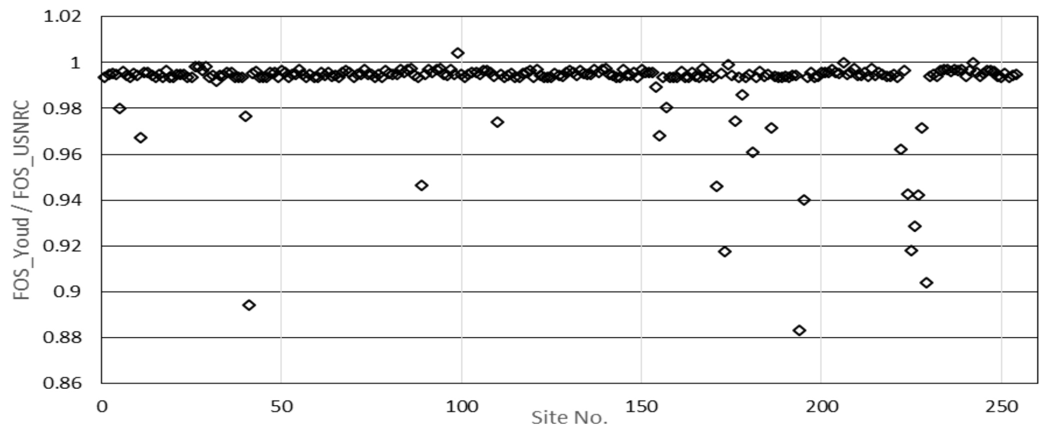

Figure-3 Ratio of FOS from Youd et al. (2001) and USNRC for case history database

Ratio of FOS calculated using Youd et al. (2001) and I&B (2014) is shown in Figure-4. FOS against liquefaction calculated using I&B (2014) vary significantly when compared to Youd et al. (2001) with ratio varying from 0.7 to 1.6. Application of Youd et al. (2001) results in higher FOS against liquefaction compared to I&B (2014) in majority cases.

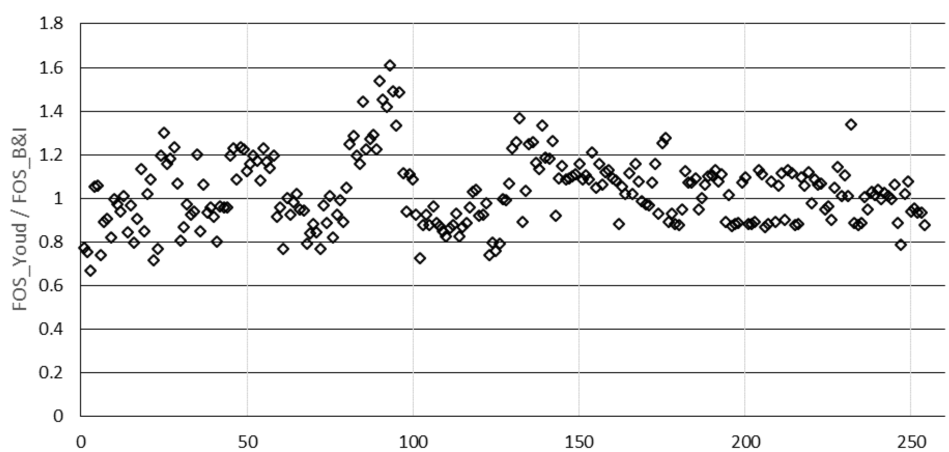

Figure-4 Ratio of FOS from Youd et al. (2001) and I&B (2014) for case history database

Accuracy of predicting liquefaction hazard

Since the empirical methods base their estimation on the case history database, prediction of liquefaction for a postulated seismic condition would have certain inherent uncertainties/ errors. Reliability of a method stems from its ability to predict with reasonable accuracy the possibility of liquefaction. In the present assessment, out of 254 case histories available, 96 are for earthquakes up to year 1981 which are part of Youd et al. (2001) database. Additional 158 case histories are from I&B (2008, 2014). Actual observation at site for these case histories (liquefaction or no-liquefaction) is taken from corresponding references.

Of the 96 records for earthquake up to year 1981, 53 cases were from liquefied sites. Out of these 53 records, Youd et al. (2001) predicts liquefaction status correctly for 47 cases and for 6 cases it predicts false negatives (i.e. it gives FOS$\geq$1, though the site actually liquefied). Of the 158 additional records post 1981, 83 records were for liquefied sites. Prediction using Youd et al. (2001) results in false negatives for 7 cases out of these 83 records. Hence, in total, Youd et al. (2001) predicts false negative for 13 cases (10%) out of 136 records for liquefied sites.

Application of I&B (2014) on the other hand, gives false negative for 2 cases out of 53 records of liquefaction before year 1981 and 4 cases for records post year 1981. Thus, in total, I&B (2014) predicts false negative for 6 cases (5%) out of 136 records of liquefied sites. Details of sites for which false negative is predicted by these methods along with corresponding FOS are reported in Table-2. Figure-5 shows the comparison of FOS for these sites in graphical form.

Examination of both methods (Youd et al. (2001) and I&B (2014)) vis-à-vis factor of safety associated with corresponding false negative predictions reveals the following:

i. Maximum FOS predicted by Youd et al. (2001) for a "liquefied" site is 1.36, whereas that by I&B (2014) is 1.25.
ii. Out of 13 sites wrongly predicted as non-liquefied by Youd et al. (2001), I&B (2014) makes correct prediction (FOS $\leq$ 1) for 7 sites. In similar way, Youd et al. (2001) makes correct prediction for 2 out of 6 sites wrongly predicted as non-liquefied by I&B (2014).
iii. Mean FOS by Youd et al. (2001) (for false negative alone) is 1.12 with a standard deviation of 0.11.
iv. Mean FOS by I&B (2014) (for false negative alone) is 1.10 with a standard deviation of 0.093.
v. Better performance by I&B (2014) may be due to the fact that all 254 case histories were part of data used by I&B (2014) for developing the methodology.

Table-2 Details of sites for which false negative prediction made by empirical methods

Site No.	Earthquake	Site	Liquefied?	FOS_Youd	FOS_I&B
1.	1964 M=7.6 Niigata earthquake - June 16	Arayamotomachi	Yes	0.79	1.07
2.	1964 M=7.6 Niigata earthquake - June 16	Rail Road-2	Yes	1.00	0.98
3.	1976 M=7.6 Tangshan earthquake - July 27	Coastal Region	Yes	1.11	1.20
4.	1978 M=6.5 Miyagiken-Oki earthquake - Feb 20	Nakamura DykeN-4	Yes	1.02	0.91
5.	1981 M=5.9 WestMorland earthquake - April 26	Kornbloom B	Yes	1.08	0.70
6.	1981 M=5.9 WestMorland	Radio Tower B1	Yes	1.21	0.85

	earthquake - April 26				
7.	1981 M=5.9 WestMorland earthquake - April 26	Wildlife B	Yes	1.29	0.87
8.	1983 M=7.7 Nihonkai-Chubu earthquake - May 26	Aomori Station	Yes	0.93	1.00
9.	1983 M=6.8 Nihonkai-Chubu earthquake - June 21	Takeda Elementary Sch.	Yes	**1.36**	**1.25**
10.	1987 M=6.2 and M=6.5 Superstition Hills earthquakes - 01 & 02 - Nov 24	Wildlife B	Yes	1.20	0.95
11.	1989 M=6.9 Loma Prieta earthquake - Oct 18	Miller Farm CMF 5	Yes	1.07	1.02
12.	1989 M=6.9 Loma Prieta earthquake - Oct 18	State Beach UC-B2	Yes	1.03	0.92
13.	1995 M=6.9 Hyogoken-Nambu (Kobe) earthquake - Jan 16	Kobe-24	Yes	1.00	0.91
14.	1995 M=6.9 Hyogoken-Nambu (Kobe) earthquake - Jan 16	Kobe-37	Yes	1.05	0.93
15.	1999 M=7.6 Chi-Chi - Sept 20	Yuanlin BH40	Yes	1.15	1.06

Figure-5 Comparison of FOS for sites where false negative prediction made by empirical methods

SUMMARY AND CONCLUSIONS

Assessment of commonly used SPT based liquefaction prediction methods is conducted in this study based on latest available liquefaction case history database. Study indicate that I&B (2014) method provides better prediction of liquefaction potential than Youd et al. (2001) when latest available database on liquefaction is considered (5% wrong prediction as against 10% of Youd et al. (2001)). This is due to the fact that I&B (2014) relationship makes use of updated database with refined analysis of various parameters. However, even after refinement of method with updated database, there are cases where I&B (2014) predicts a liquefied site as non-liquefied. This could be due to uncertainty in various procedures/empirical relations, as adopted in empirical method of liquefaction evaluation. In order to account for uncertainties associated with empirical methods, minimum acceptable FOS shall be higher than 1.0 with suitable margin. This issue becomes more important with respect to safety of NPPs because liquefaction induced ground failure can cause wide spread damage to the plant SSCs rendering structural redundancies ineffective, which are otherwise available during local structural failure.

Following conclusions are made in this study:

i. Among different types of in-situ tests used for assessment of liquefaction potential, because of the more extensive databases and past experiences, standard penetration test (SPT) is seen to be a preferred choice.
ii. Subsequent to publication of regulatory guidelines by USNRC [USNRC RG 1.193, 2003], case history database for liquefaction has been augmented and updated by many researchers (158 additional records are added to the database subsequent to USNRC (2003) making total 254 number of case histories). Though a pioneering work in terms of development of methodology and criteria for regulatory acceptance was undertaken by USNRC, in light of updated database and further research work available in literature, the methodology proposed in USNRC (2003) may need to be revisited and modified. Similarly, state of the art requirements needs to be reflected in other appropriate regulatory documents such as IAEA NS-G-3.6 (2004).
iii. I&B (2014) method is updated and uses more refined analysis for LHA and seems to be a better choice compared to Youd et al. (2001)/ USNRC (2003) methods based on the results in this study.
iv. Even after refinement of method with updated database by I&B (2014), there are case histories where it predicts a liquefied site as non-liquefied. This is due to uncertainty in various procedures/empirical relations as adopted in empirical method of liquefaction evaluation.
v. Outcome of this study indicates that, to address the uncertainties in empirical methods, more than one method, which are state-of-art, should be used. Envelope of the results from these methods should be used for regulatory decision making.
vi. Factor of safety representing liquefaction potential should be conservatively estimated. Based on the assessment of Youd et al. (2001) and I&B (2014), it is observed that FOS of 1.0 does not always guarantee non-liquefaction. Considering the uncertainties in these methods, acceptance criteria against liquefaction should be decided taking into account hazard potential of the project.

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