Deterministic and probabilistic liquefaction potential evaluation of Guwahati city

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ABSTRACT

Northeastern region of India is one of the six most seismically active regions of the world. Guwahati, the major city in the region is growing rapidly in every aspect. The 1897 great Assam earthquake and the 1950 Assam earthquake both of magnitude 8.7 are two of the many great earthquakes that had occurred in this region. There have been reports of extensive liquefaction occurring during these two earthquakes. These instances of liquefaction necessitate the need to evaluate liquefaction potential of the area. In the present study, an attempt has been made to predict the liquefaction susceptibility of Guwahati city based on corrected standard penetration test (SPT) N values using deterministic as well as probabilistic performance based approach. The deterministic and probabilistic version of Toprak et al., Youd et al., Idriss and Boulanger and Cetin, SPT N based liquefaction triggering correlations have been used. The results obtained in the probabilistic approach are then compared with their deterministic approach. Standard penetration test (SPT) N values, engineering properties of the soils and depth of water table were taken from a data base of 200 boreholes upto 30 meter depth covering an area of 262 km² in Guwahati city. Liquefaction susceptibility from the methods is presented as maps showing zones of levels of risk of liquefaction. Comparison of the three methods in the deterministic approach have shown that there is a difference in the factors of safety in the same depth and comparison in the probabilistic approach have also shown a difference in the values of probabilities in the same depth. The SPT - based liquefaction evaluation procedures have been found to yield significantly different predictions. This study feels that the issues and uncertainties regarding the use of both the deterministic and probabilistic liquefaction triggering relationships in practice must be resolved so as to arrive at a common consensus to determine the same.

Keywords: earthquake, geotechnical engineering, liquefaction, deterministic, probabilistic method, evaluation

1 INTRODUCTION

Northeastern region of India lying at the junction of the Himalayan arc to the north and the Burmese arc to the east, is one of the six most seismically active regions of the world. There have been reports of extensive liquefaction occurring during the 1897 great Assam earthquake and the 1950 Assam earthquake both of magnitude 8.7. Determination of the liquefaction potential of the cohesionless deposits in Guwahati is therefore important for the design of new structures and lifeline systems.

Different research developments in determination of liquefaction potential have evolved due to the continued effort of many research workers in the past few decades. The liquefaction potential may be expressed as factor of safety (FOS) or probability of liquefaction (PL). Determination of the probability of liquefaction is important for assessment of the performance based earthquake engineering. Compared to factor of safety, the probability of liquefaction is more suitable as an index for assessment of liquefaction potential and for liquefaction potential mapping. In the deterministic approach, the standard penetration test (SPT) along with the semi-empirical equations and models (giving liquefaction boundary curves) is widely used to determine liquefaction susceptibility of a soil. The stress-based approach, developed by Seed and Idriss (1967), has been used for the last four decades (e.g., Seed and Idriss (1971), Tokimatsu and Yoshimi (1983), Seed et al. (1985), Yound et al. (2001) Cetin et al. (2004), Idriss and Boulanger (2004, 2008). This approach assesses the cyclic stress ratio (CSR) anticipated at the site during a certain design earthquake and compares to that required to produce liquefaction (CRR).

The cyclic stress ratio (CSR) anticipated at the site during a certain design earthquake is estimated by using the simplified procedure pioneered by Seed and Idriss (1971) (Eq. 2 in Appendix A). The soil’s CSR is affected by the duration of shaking (which is expressed through an earthquake magnitude scaling factor, MSF), effective overburden stress (which is expressed through a Kc factor). These effects are accounted for in the processing of case histories by adjusting the earthquake-induced CSR to a reference M = 7.5 and σv' = 1atm. The soils CSR are also affected by rM, a stress reduction coefficient that
accounts for the flexibility of the soil column.

Cyclic resistance ratio (CRR) is defined as the ratio of the cyclic strength of the soil over the effective overburden pressure. Liquefaction is likely if the cyclic stress ratio (CSR) exceeds the cyclic resistance ratio (CRR). As discussed by Youd et al. (2001), one of the most widely used SPT-based correlations to determine CRR is the “deterministic” relationship proposed by Seed et al. (1984, 1985). This relationship is based on comparison between SPT N values, corrected for both effective overburden stress and energy, equipment and procedural factors affecting SPT, i.e., \( (N_{1})_{60cs} \) to the cyclic resistance value (CRR) of the soil. The NCEER/NSF workshop in 1996/98 recommended some revisions to the SPT-based procedure but with only minor adjustments to the CRR – \( (N_{1})_{60cs} \) curve for clean sands put forth by Seed et al. (1984). Since the semi-empirical liquefaction correlations are based primarily on data for effective overburden stresses in the range of 100 \( \pm \) kPa and for a \( M = 7.5 \) earthquake, Seed (1983) recommended that the CRR be corrected for these effects using the following expression.

\[
CRR = CRR_{M=7.5,\sigma_v=1} \times MSF \times K_{\sigma}
\]

In the deterministic approach, factor of safety (FOS) is defined as CRR/CSR. Generally, the minimum acceptable factor of safety is in between 1.25 to 1.50 (Seed and Idriss (1985)).

Probabilistic approach is used to assess the probability of initiation of liquefaction. Standard penetration test (SPT) based probabilistic correlations for the initiation of liquefaction in sands and silty sands have been derived by a number of investigators, Liao et al. (1988), Liao and Lum (1998), Youd and Noble (1997), Toprak et al. (1999), Juang et al. (2002), Cetin et al. (2002, 2004), Moss et al. (2006) and Idriss and Boulanger (2012). The SPT-based relationships by Toprak et al. (1999), Cetin et al. (2004) and Idriss and Boulanger (2012) show curves of the cycle stress ratio (CSR) \( CSR_{M=7.5,\sigma_v=1} \) versus \( (N_{1})_{60cs} \), corresponding to probabilities of liquefaction (PL) of 5-95%, where \( CSR_{M=7.5,\sigma_v=1} \) is the CSR adjusted to an equivalent earthquake magnitude of \( M = 7.5 \) and vertical effective stress of \( \sigma_v' = 1 \) atm, and \( (N_{1})_{60cs} \) is the equivalent clean-sand SPT blow count corrected to an equivalent energy ratio of 60% and vertical effective stress of 1 atm.

The SPT-based probabilistic relationships by Toprak et al. (1999), Cetin et al. (2004) and Idriss and Boulanger (2012) can be expressed by single, composite relationships which are functions of SPT N value, CSR, moment magnitude (M), Fine content (FC) and vertical effective stress shown in Appendix A.

Both deterministic and probabilistic SPT based procedures from Cetin (2004), Idriss and Boulanger (2004, 2012) and Toprak (1999) are compared in this study with a data base of 200 bore holes of Guwahati city. The bore holes were of 30m depth and it covered an area of 262 km².

In Toprak (1999), the adjustments for the magnitude scaling factors and for \( (N_{1})_{60cs} \), were done according to Youd and Idriss (1997).

The stress reduction, \( r_s \), proposed by Cetin et al. (2004) was developed based on a much higher number of cases (2,153 site response analysis cases). The stress reduction factor was expressed as a function of depth, earthquake magnitude, ground acceleration and the average shear wave velocity of the top 12 m soil column. The average shear wave velocity of the top 12m soil column has been taken for this study from Sharma B et al. (2013).

2 THE STUDY AREA

The Guwahati city area lying between latitude 26.1833° N and longitude 91.733° E measures about 229.94 km² encompassing southern part of Kamrup (Urban) district of Assam. The mighty river Brahmaputra flows to the north of Guwahati city, the south and the eastern sides are surrounded by two rows of semi-circular hillocks.

A soil database from 200 boreholes was used to determine factors of safety against liquefaction and probabilities of liquefaction for areas in Guwahati city. The soil database was from a project funded by the Directorate of Science and Technology, India for Microzonation of Guwahati City. Bore holes of 30m depth were made in 200 locations and standard penetration test was done at every 1.5m interval upto 30m. The bore hole locations along with the river Brahmaputra in Guwahati city are shown in Fig.1 to 3. SPT-N value of the soils varied from 4 to > 50 (refusal). Soils in Guwahati mostly consist of alluvial deposits consisting of alternating layers of both fined grained and coarse grained soils. There is a great deal of variation in the thickness of these layers. The fine grained fraction mostly consists of red, brown and grey coloured silty clay and clay of classification SP, SW, SC, SM, SP-SC. The 200 boring logs showed the water table to be within 0–6 m of the ground surface. For the probabilistic determination of liquefaction potential of Guwahati city, three probabilistic models, of Cetin et al. (2004), Idriss and Boulanger (2012) and Toprak et al (1999), consisting of standard penetration test (SPT) based liquefaction triggering correlations have been used. The deterministic liquefaction triggering correlation
by Idriss and Boulanger (2004), Cetin (2004) and Youd and Idriss (2001) have been used to determine the factor of safety of the soils. The equations used for the analysis are shown in Appendix A.

In this study the soil layers that were identified for liquefaction analysis are fine to medium sand and silty sands that have classification of SP, SW, SC, SM, SP-SC. Inorganic silt of classification ML, ML-CL and non plastic inorganic silts were also analysed for liquefaction susceptibility. Of the 200 number of bore holes, 92 number of bore holes were found to have such soil layers. Seed et al. (1983) stated that based on laboratory testing and field performance, the great majority of cohesive soils will not liquefy during earthquakes. Of the 200 number of bore holes, 49, 49 and 51 number of bore holes were found to be susceptible to liquefaction according to the deterministic models of Idriss and Boulanger (2004), Youd et al. (2001) and Cetin et al. (2004) respectively. The lowest factor of safety against liquefaction among the layers is retained as the factor of safety for that bore hole. Liquefaction susceptibility from the methods is presented as maps showing zones of levels of risk of liquefaction. Fig.1 shows liquefaction potential map of Guwahati city according to the deterministic approach of Cetin et al. (2004).

Figures 2, 3 and 4 show the map according to the probabilistic approach of Cetin et al. (2004), Idriss and Boulanger (2004), and Toprak et al. (1999) respectively. The probability in percentage and factor of safety with depth are shown from Figs. 5 to 7 for an earthquake magnitude of 7.5 for three bore holes of the 92 bore holes analyzed. It is observed in bore hole 12 that from depths 7.5m to 16.5m the factor of safety according to the deterministic models are less than 1.
Probabilistic models confirm this result with very high scale of severity i.e. 100% PL. Similarly in other bore holes where the factor of safety is greater than 1.5, the probabilistic models confirmed this result with zero or insignificant liquefaction probability (PL). Similarly there is agreement between the probabilistic and the deterministic models in bore hole 2, 8 and the other bore holes analysed. However, it is observed that there is variation in the percentage of probability in the three probabilistic models. Similarly there is variation in the factor of safety in the three deterministic models. There is also difference in the factors of safety in the same depth and also there is difference in the values of probabilities in the same depth. In the 92 bore holes analyzed, the average % deviation in probability between Cetin et al. (2004) and Toprak et al. (1999) is 18.58%, between Toprak et al. (1999) and Idriss and Boulanger (2012) is 26.7% and between Idriss and Boulanger (2012) and Cetin et al. (2004) is 27.3%. Similarly the average % deviation in factor of safety between Cetin et al. (2004) and Youd et al. (2001) is 36.72%, between Youd et al. (2001) and Idriss and Boulanger (2012) is 25.48% and between Idriss and Boulanger (2012) and Cetin et al. (2004) is 37.93%. This variation is further clear in Figs. 8 and 9. The factor of safety according to Cetin et al. (2004) is significantly lower than those by Youd et al. (2001) and those by Idriss and Boulanger (2004, 2008).

The relationship by Cetin et al. (2002, 2004) incorporated model and measurement uncertainties. The relationship by Toprak et al. (1999) is a simplified probabilistic model which incorporated the model uncertainties and the uncertainty in the \((N_1)_{60cs}\) and CSR values determined for the case histories. The Idriss and Boulanger (2012) probabilistic liquefaction triggering correlations were derived using a reassessed updated case history database. The relationship incorporated measurement or estimation uncertainties in CSR and \((N_1)_{60cs}\) for the case histories and choice-based sampling bias were also accounted for in the derivation of the relationship. The database by Idriss and Boulanger (2012) consists of 227 cases, out of which 115 are nonliquefied cases and 112 are liquefied cases. The database developed by Idriss and Boulanger (2012) is regarded as an update of the Cetin et al. (2004) database, although different opinions exist for some cases.

It should be noted that Idriss and Boulanger (2004, 2006) did not suggest an upper bound for \((N_1)_{60CS}\) in the CRR formulation. This equation represents an extrapolation when \((N_1)_{60CS} > 32\), which could be subjected to error. In the latest NCEER study (Youd et al., 2001) the CRR formulation has an upper bound of \((N_1)_{60CS} = 34\). The SPT- based liquefaction evaluation procedures have been found to yield significantly different predictions. This is found to create some confusion in the minds of practicing engineers working in the field of soil liquefaction. This study feels that the issues and uncertainties regarding the use of both the deterministic and probabilistic
liquefaction triggering relationships in practice must be resolved so as to arrive at a common consensus to determine the same.

Fig. 8. Comparison of factor of safety against liquefaction for BH-7, 8, 12 and 16 obtained using different methods for M = 7.5.

Fig. 9. Comparison of probability of liquefaction for BH-7, 8, 12 and 16 obtained using different methods for M = 7.5.

3 CONCLUSIONS

In the present study, an attempt has been made to predict the liquefaction susceptibility of Guwahati city based on corrected SPT values using three deterministic as well as three probabilistic performance based approach. Liquefaction susceptibility from the methods is presented as maps showing zones of levels of risk of liquefaction. The SPT-based liquefaction evaluation procedures have been found to yield significantly different predictions. There is also difference in the factors of safety in the same depth and also there is difference in the values of probabilities in the same depth. The factor of safety according to Cetin et al. (2004) is significantly lower than those by Youd et al. (2001) and those by Idriss and Boulanger (2004, 2008). This study feels the differences in the predictions of probability of liquefaction and factor of safety against liquefaction must be resolved so as to remove confusion in the minds of practicing engineers working in the field of soil liquefaction.

ACKNOWLEDGEMENT

The geotechnical data of the 200 boreholes were taken from a project work given to Assam Engineering College, titled ‘Liquefaction potential determination of Guwahati city’ funded by the Directorate of Science and Technology (DST), India for Microzonation of Guwahati city. We acknowledge the help and assistance given by DST, India for the study.

APPENDIX A

The CSR is the adjusted cyclic stress ratio defined as:

$$CSR = 0.65 \left( \frac{\sigma_v}{\sigma_y} \right)^{0.68} \left( \frac{g \, W}{M} \right)^{0.68} \left( \frac{1}{K_{CSN}} \right)^{0.68}$$

According to Idriss and Boulanger (2004, 2005), cyclic resistance ratio (CRR) is computed as:

$$CRR = \left( \frac{N_i \sigma_{v, o}}{N_i \sigma_{y, o}} \right)^2 \exp \left( -\frac{\left( \frac{N_i \sigma_{v, o}}{2.3 \times 1.4} \right)^4 + \left( \frac{N_i \sigma_{v, o}}{25.4 \times 25} \right)^4}{2.8} \right)$$

Idriss and Boulanger (2012) model:

$$PL = \left( N_i \right)_{o, o} \left( \frac{CSR}{\sigma_y} \right)^{\frac{\sigma_y}{\sigma_c}} \left( \frac{\sigma_y}{\sigma_c} \right)^{\frac{\sigma_y}{\sigma_c}} \exp \left( -\frac{\ln \left( \frac{CSR}{\sigma_y} \right)}{0.05 FC + 0.1685} \right)$$

Cetin et al. (2004) model:

$$PL = \left( N_i \right)_{o, o} \left( 1 + 0.004 \left( FC \right) \right) \left( 1 + 0.004 \left( FC \right) \right) \left( 1 + 0.004 \left( FC \right) \right)$$

The cyclic resistance ratio for a given probability of liquefaction is expressed as:

$$CRR = \left( \frac{N_i \sigma_{v, o}}{N_i \sigma_{y, o}} \right)^2 \exp \left( -\frac{29.53 \ln (M) + 3.7 \ln \left( \frac{\sigma_y}{\sigma_c} \right)}{0.05 FC + 0.1685 + 2.7 \Phi^{-1} (PL)} \right)$$
Where, \( \phi^{-1}(\text{PL}) \) = inverse of the standard cumulative normal distribution (i.e., mean = 0, and standard deviation = 1).

**Toprak (1999) model**

The logistic regression equation obtained from the new world wide liquefaction database (total number of data points = 440):

\[
\text{Logit} \left( \frac{\text{PL}}{1 - \text{PL}} \right) = 10.4459 - 0.2295 (N_i)_m - 0.0573 \frac{\text{CSR}}{\text{MSF}}
\]

All CSRs were adjusted to \( M_W = 7.5 \) using the Idriss MSF. Idriss MSF values should be used in above equation to get probabilistic curves for earthquakes with different magnitudes. The definitions of different terms used in the Eqs. (2) to (7) are given in Idriss and Boulanger (2004, 2012), Cetin et al. (2004) and Toprak et al. (1999).

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