ASSESSMENT OF LIQUEFACTION POTENTIAL FOR KARNATAKA STATE USING PROBABILISTIC APPROACH

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ABSTRACT: Liquefaction is a phenomenon, in which the loose, cohesionless, saturated soil loses its shear strength due to huge pore pressure build up under earthquake loading. Soil tends to flow like viscous liquid and the bearing capacity reduces dramatically inducing settlement failure in the buildings. Classic scenario of liquefaction failure in India was observed during Bhuj earthquake 2001. For the mitigation of liquefaction, first step is to evaluate the liquefaction potential of soil in the site, which can be done using laboratory and field tests. Practical difficulties in obtaining undisturbed sample and expensive test setups, made the assessment of liquefaction potential using field tests like SPT and CPT are more attractive. In this paper, considering peak horizontal acceleration for site class D soil profile, SPT and CPT values required to prevent liquefaction for the entire state of Karnataka is predicted using a probabilistic methodology. Spatial variation of SPT and CPT values required for preventing liquefaction for a return period of 475 and 2500 years at depths of 3m are presented in this paper.

INTRODUCTION
Liquefaction is one of the major devastating effects of earthquake. It was first observed during the 1964 Alaska (Mw = 9.2) and Niigata (Ms = 7.5) earthquakes [1]. Major damages like, slope failure, bridge and building foundation failure and collapse of buried structures during above earthquakes were mainly due to liquefaction. In India, damages due to liquefaction were observed during Bhuj earthquake (Mw 7.7) of 2001. Thus assessment of liquefaction hazard is essential and it forms the foremost step for the planning of any mitigation works. The most widely accepted methodology for assessing liquefaction potential was proposed by [2] where factor of safety against liquefaction is based on the ratio of cyclic shear strength of soil to the cyclic stress induced in soil during earthquake. The evaluation of cyclic shear strength of soil requires laboratory testing like cyclic triaxial test, cyclic torsional test on undisturbed soil sample.

Evaluation of liquefaction potential based on field tests have gained much popularity due to the difficulties associated with obtaining good soil samples for laboratory testing. Major in-situ tests are the standard penetration test (SPT), cone penetration test (CPT), shear wave velocity test (Vs) and the Becker penetration test (BPT) [3]. SPT being an inevitable part of soil investigation for civil engineering constructions, evaluation of liquefaction potential in terms of SPT value will be very beneficial for geotechnical engineers to make quick evaluation of liquefaction hazard for the sites from known SPT value. Whereas, the main advantage of using CPT data is that the percentage of errors is considerably less than that of SPT method. In this paper, liquefaction potential for the entire state of Karnataka is presented in terms of SPT and CPT values and its spatial variation is also shown.

STUDY AREA
Region selected for the study is the state of Karnataka which forms a part of south India, located between 74° 6’ E and 78° 35’ E longitude and 11° 37’ N and 18° 28’ N latitude. The state covers an area of 1,91,791 km², 5.83% of the total geographical area of India. Major cities in the Karnataka state are under rapid urbanization process. In capital city Bangalore, many infrastructural development activities like Metro rail projects have already been initiated. Hence, the occurrence of soil liquefaction during earthquake can cause significant damages in these cities. This clearly indicates that for the state of Karnataka, liquefaction assessment studies are essential.

SEISMIC HAZARD ASSESSMENT OF THE STUDY AREA
A probabilistic seismic hazard analysis [4] is used for the evaluation of seismic hazard for the study area. For this, all the earthquake events and sources within the 300 km from boundary of Karnataka are collected from various agencies. All events are converted into moment magnitude scale (Mw) using suitable relations proposed by [5] [6] and [7].

Fig.1. Seismotectonic atlas for the study area
These events are then declustered so that the resulting data base is to be free from repetitive events, foreshocks, aftershocks [8]. After declustering, there are about 1678 seismic events in the study area and out of which 555 events are of magnitude 4 and above. Typical map showing all faults and events in the study area is presented in fig. 1.

Seismicity Analysis
The seismicity of the study area is assumed to follow using Gutenberg - Richter recurrence law [9]. Gutenberg – Richter seismicity parameters ‘a’ and ‘b’ for the study area are evaluated using statistical methodology proposed by [10]. The ‘a’ and ‘b’ are found to be 4.475 and 0.893 respectively which is comparable with that of early studies by [8] for south India and [11] for Bangalore.

Hazard Analysis
Peak horizontal acceleration at bed rock level for the entire study area is obtained using probabilistic seismic hazard analysis incorporating logic tree methodology.

Two types of seismic sources— linear and areal sources [12] and three attenuation models proposed [13, 14] and [15] are used for the estimation of hazards. Equal weightages of 0.5 are given to both the source model. For attenuation relations, [13] is given a higher weightage of 0.4 and weightage of 0.3 is given to attenuation model proposed by [14] and [15] respectively. The state of Karnataka is divided into small grids of 0.050 X 0.050 (approx. 5km X 5km) and the hazard is evaluated at the center of grid by considering the sources within 300 km radius of the grid boundary. This is done with a MATLAB program (Vipin 2010).

Assessment of liquefaction based on SPT and CPT values requires knowledge of surface level peak horizontal acceleration for soil profile pertaining to site class D. Assuming the soil above bed rock of the whole region belonging to site class D, as per [16] (National Earthquake Hazard Research Programme) and [17] (International Building Code) recommendation, the ground motion at surface level for each site is obtained by multiplying suitable amplification factor suggested for peninsular India by [13], to the bedrock motion.

PROBABILISTIC ASSESSMENT OF LIQUEFACTION POTENTIAL BASED ON SPT VALUES
Liquefaction potential of soil at a particular can be evaluated by laboratory and field testing. As it’s very difficult of get an undisturbed sample from the field, laboratory testing becomes uneconomical and unpractical in major cases. Thus field testing is much easier way of evaluating liquefaction procedure and in India the most popular field testing is standard penetration test (SPT).

The evaluation of liquefaction potential involves two stages – (i) evaluation of earthquake loading based on cyclic stress ratio (CSR) and (ii) evaluation of soil strength against earthquake loading based on SPT and CPT values required to resist liquefaction.

Seed and Idriss [2] suggested a simplified of evaluating earthquake loading as per equation 1.

\[
\text{CSR} = 0.65 \left( \frac{a_{\text{max}}}{g} \right) \left( \frac{\sigma_{\text{o}}}{\sigma'_{\text{o}}} \right) \left( r_d / \text{MSF} \right)
\]

Here \(a_{\text{max}}\) is peak ground acceleration (surface level for site class D); \(\sigma_{\text{o}}\) and \(\sigma'_{\text{o}}\) are total and effective over burden pressure; \(r_d\) is depth reduction factor. [18] proposed modified \(r_d\) which is function of depth (d), incremental values in earthquake magnitude (\(m_d\)) and acceleration level (\(a_i\)) and average shear wave velocity for top 12 m (\(V_{12}\)) in order to capture the contribution from several magnitude and acceleration level.

Liquefaction potential can be characterized by the SPT resistance required to prevent liquefaction, \(N_{\text{req}}\). The mean annual rate of exceedance (\(\lambda_{N_{\text{req}}}\)) of number of blows \(N_{\text{req}}\) can be estimated using equation 2 suggested by [19].
Assessment of liquefaction potential for the Karnataka state using probabilistic approach

\[ \lambda_{N*_{req}} = \sum_{i=1}^{N_a} \sum_{j=1}^{N_m} P[N_{req} > N^*_{req} | a_i, m_j] \Delta \lambda_{a_i, m_j} \]  \hspace{1cm} (2)

Here, \( a_i \) and \( m_j \) are the incremental values in earthquake magnitude and acceleration level and the probability of \( N_{req} \) exceeding a predefined value of \( N^*_{req} \) is given by equation 3 as per [18]. \( \Delta \lambda_{a_i, m_j} \) is the incremental annual frequency of exceedance for acceleration \( a_i \) and magnitude \( m_j \) and \( P[N_{req} > N^*_{req} | a_i, m_j] \) is given by equation 3 as per [20].

\[ P[N_{req} > N^*_{req} | a_i, m_j] = \Phi \left( \frac{N_{req} - 0.13 \lambda \sigma_{v} (\lambda \sigma_{v} - 0.85 \lambda \sigma_{v} - 0.001 \lambda \sigma_{v} - 0.001 \lambda \sigma_{v})}{0.13 \lambda \sigma_{v}} \right) \]  \hspace{1cm} (3)

Here, \( \lambda_{a_i, m_j} \) is the incremental annual frequency of exceedance for acceleration \( a_i \) and this will be calculated for all the acceleration levels. \( \theta \)’s - are the regression coefficient. \( N^*_{req} \) is the corrected \( N \) value (for energy, overburden pressure and percentage of fines) required to prevent liquefaction with an annual frequency of exceedance of \( \lambda_{N^*_{req}} \) and \( \Phi \) - is cumulative normal distribution. From the mean annual exceedance curve, SPT values required to prevent liquefaction can be estimated.

**Based on CPT Values**

Similar to SPT based liquefaction assessment, CPT based analysis was also carried out for the entire state of Karnataka. The main advantage of using CPT data is that the percentage of errors is considerably less than that of SPT method. The mean annual rate of exceedance (\( \lambda_{c_i, c_j} \)) of CPT value (\( q_c \)) required to resist liquefaction is given as per equation 4.

\[ \lambda_{c_i, c_j} = \sum_{i=1}^{N_a} \sum_{j=1}^{N_m} P[q > q^*_{c, c_j} | a_i, m_j] \Delta \lambda_{a_i, m_j} \]  \hspace{1cm} (4)

Here, \( q^*_{c, c_j} \) is the targeted value; \( N_{m_j} \) number of magnitude increments; \( N_a \) number of peak ground acceleration; \( \Delta \lambda_{a_i, m_j} \) is the incremental annual frequency of exceedance for acceleration \( a_i \) and magnitude \( m_j \). Now \( P[q > q^*_{c, c_j} | a_i, m_j] \) is given by equation 5 as per [22].

\[ P[q > q^*_{c, c_j} | a_i, m_j] = \Phi \left( \frac{q^*_{c, c_j} - q^*_{c, c_j} (0.110R) - 0.001R - 0.101R - 0.001R - 0.001R)}{0.110R} \right) \]  \hspace{1cm} (5)

From the mean annual exceedance curve, CPT values required to prevent liquefaction can be estimated.

**RESULTS AND DISCUSSION**

In order to consider the worst scenario for the liquefaction analysis, the water table was assumed at the ground surface. The SPT and CPT values required to prevent liquefaction was predicted for the entire state of Karnataka and its spatial variation is presented.

![Fig. 5 SPT values required to prevent liquefaction (475 years return period) at 3m depth](image1)

![Fig. 6 SPT values required to prevent liquefaction (2500 years return period) at 3m depth](image2)

![Fig. 7 CPT (MPa) values required to prevent liquefaction ((a) 475 years and (b) 2500 years return period) at 3m depth](image3)

From fig. 5 and fig. 6, the SPT value required to prevent liquefaction is less than 10, which implies that if the average SPT value at 3m depth is greater than 10, then the site will not liquefy for a time period of 475 years. Places like Bangalore, Mysore require SPT value of 10 and above to resist liquefaction for a period of 475 years. For the interior regions in Karnataka, the SPT value required to resist liquefaction falls in the range of 3 to 10. Fig. 7(a, b) shows the spatial variation of CPT values (MPa) required to resist liquefaction for a return period of 475 years. CPT values required to prevent liquefaction for the places like Bidar and Bangalore are more than 10 MPa. CPT values ranging from 3 MPa to...
10 MPa is good enough to resist liquefaction for interior regions of Karnataka.

CONCLUSIONS
In this paper, an attempt is made to expresses the liquefaction potential for the entire state of Karnataka in terms of SPT values. The uncertainty in earthquake loading was well accounted by considering all the combinations of accelerations - magnitudes values for the evaluation of liquefaction potential. For site class D condition, the SPT \([(N_1)_{60}, c_s] \) and CPT (MPa) required to prevent liquefaction was evaluated at 3m depths, for the entire state of Karnataka.

Thus studies show that these regions are having high chance to get liquefy if any site in this region belong to site class D and water table is at shallow depth. Present study indicates that the interior region in the state is having low liquefaction hazard compared to regions close to Bidar, Bangalore and Konkan belt.

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