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LIQUEFACTION POTENTIAL EVALUATION BASED ON SITE CLASSES – A PERFORMANCE BASED APPROACH

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ABSTRACT

Lots of research work is being carried out in evaluating the liquefaction susceptibility. The main objectives of these studies are to identify the regions which are vulnerable to liquefaction. In the present study, an attempt has been made to predict the liquefaction susceptibility based on corrected SPT values required to prevent the liquefaction for given return periods. The evaluation of liquefaction susceptibility requires the calculation of two parameters, seismic loading and the soil resistance. In most of the studies, the seismic loading will be evaluated based on probabilistic methods and the evaluation of soil resistance will be done based on deterministic analysis. In the present study these parameters were evaluated based on the probabilistic methods. The contour curves showing the spatial variation of SPT values required to prevent the liquefaction for return periods of 475 and 2500 years are presented here. The liquefaction hazard curves, based on SPT values for some of the selected cities in the study area are also presented here.
Key words: seismic hazard, performance based approach, SPT, liquefaction return period

INTRODUCTION

The term liquefaction can be defined, in a broad manner, as the strength loss of saturated sands due to the sudden increase in pore water pressure. Soil liquefaction has been observed during the earthquakes due to the sudden dynamic earthquake load. The devastating effects of liquefaction were observed during the Niigata and Alaska earthquakes in 1964. These instances of liquefaction have initiated lots of research work in the area of liquefaction potential evaluation. On a broad scale the evaluation of liquefaction potential involves two steps. The first step is the evaluation of earthquake loading and the second step is the evaluation of soil resistance to liquefaction. The evaluation of earthquake loading requires the analysis of seismotectonic properties of the region, collection of earthquake details and evaluation of peak ground acceleration. Where as the soil resistance depends on the properties of soil, age and type of soil deposit and depth of ground water table. Hence the evaluation of liquefaction potential can be considered as an interdisciplinary study. The important steps involved in the liquefaction potential evaluation are:

- evaluation of peak horizontal acceleration (PHA) at bed rock level.
- evaluation of surface level peak ground acceleration (PGA), considering local site effects.
- evaluation of liquefaction potential based on the PGA values and the soil properties.

Most of the conventional liquefaction evaluation methods use single ground acceleration and earthquake magnitude values. The evaluation of seismic hazard using the probabilistic seismic hazard analysis (PSHA) shows that a particular ground acceleration was not contributed by a single earthquake magnitude, instead it has been contributed by different magnitudes with varying probability of occurrence. A new probabilistic performance based approach, based on SPT values, suggested by Kramer and Mayfield (2007) utilizes the entire ground acceleration range in evaluating the liquefaction potential. This paper deals with evaluating the liquefaction return period based on SPT values for south India by considering the uncertainties in earthquake loading and the liquefaction potential is evaluated based on a probabilistic performance based approach.

SEISMIC HAZARD ANALYSIS

The liquefaction potential evaluation was done for south India (8.0° N - 20° N; 72° E – 88° E), which is a part of the Peninsular Indian continental shield region. South India (Fig. 1) is spread over an area of one million square kilometre and with a population of 300 million. The seismic hazard analysis for the study area was done based on the probabilistic approach. The first step in seismic hazard analysis is to prepare the earthquake catalogue for the study area. Earthquakes which are occurring outside the study area will also contribute to the seismic hazard in the study area. Hence the earthquake data were collected from an area which is with in a radius of 300 km from the boundary of the study area (Regulatory guide, 1997). Since a complete earthquake catalogue for the study area was not available, it was prepared by compiling the data from different sources till December 2006. The final earthquake catalogue consists of 1955 earthquake events out of which 673 events were having magnitude 4 and above.

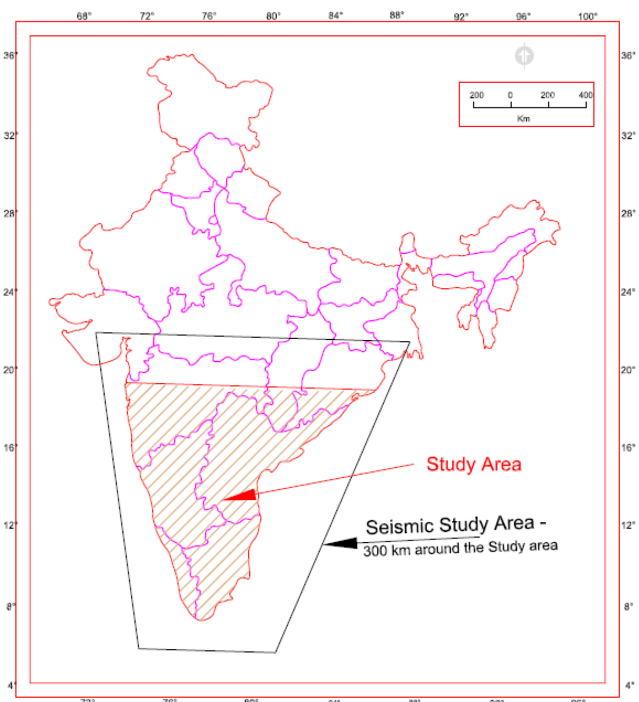

Fig.1 Location of study area in India

The earthquake recurrence rate is expressed by the Guttenberg and Richter (1944) relation.

$$Log_{10} N = a - bM \tag{1}$$

Where N is the total number of earthquakes with magnitude greater than or equal to M and "*a*" and "*b*" are the seismicity parameters for the region. These values signify the background seismicity and the magnitude size distribution for the region respectively.

The next step in the hazard analysis is to identify the vulnerable seismic sources in the study area. The sources (faults) were identified from the seismotectonic atlas (SEISAT, 2000), which contains the details of the faults, lineaments and shear zones in India and adjoining areas. The required pages of SEISAT were scanned and after georeferencing these images the earthquake data was superimposed on this. The sources, which were associated with earthquake events of magnitude 4 and above, were identified as vulnerable seismic sources and they were used in the subsequent analysis. Apart from this some more seismic sources which were identified using the remote sensing techniques (Ganesh Raj and Nijagunappa, 2004) were also used in this study. The seismic sources used in this study along with the earthquake with magnitude 4 and above are shown in Fig. 2.

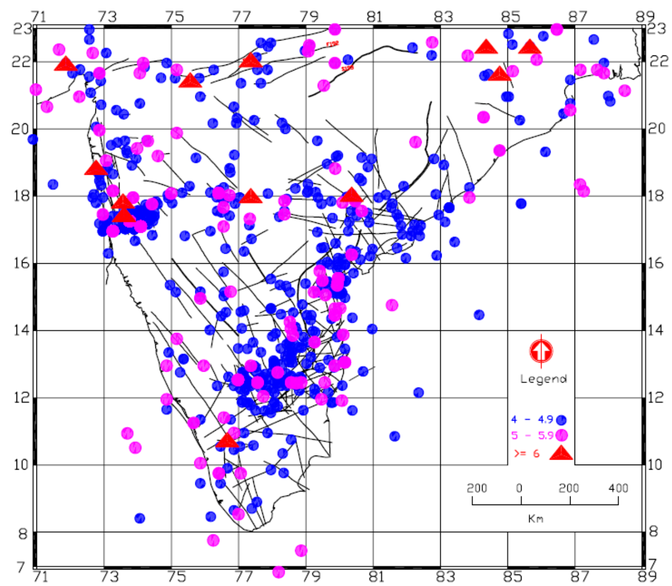

Fig. 2 Details of seismic sources considered in the seismic hazard analysis.

The mean annual rate of exceedance of ground motion parameter, Z, with respect to z for an earthquake of magnitude m occurring at a distance of r can be evaluated using the following equation.

$$\nu(z) = \sum_{n=1}^{N} N_n(m_0) \int_{m=m^0}^{m^u} f_n(m) \left[\int_{r=0}^{\infty} f_n(r \mid m) P(Z > z \mid m, r) dr \right] dm \tag{2}$$

Where N_n (m_0) is the frequency of earthquakes on a seismic source n, having a magnitude higher than a minimum magnitude m^0; $f_n(m)$ is the probability density function for a minimum magnitude of m^0 and a maximum magnitude of m^u; $f_n(r|m)$ is the conditional probability density function for the occurrence of an earthquake of magnitude m at a distance r from the site for a seismic source n; $P(Z>z|m, r)$ is the probability at which the ground motion parameter Z exceeds a predefined value of z, when an earthquake of magnitude m occurring at a distance of r from the site. Thus the function

$\nu(z)$ incorporates the uncertainty in time, size and location of future earthquakes and uncertainty in the level of ground motion they produce at the site.

The attenuation characteristics of the study area were modeled using the relation suggested by Raghu Kanth and Iyengar (2007) as this was the only attenuation relation available for the study area at present.

$$\ln y_{BR} = c_1 + c_2(M-6) + c_3(M-6)^2 - \ln R - c_4 R + \ln(\in) \qquad (3)$$

Where y_{BR} – peak horizontal acceleration (PHA) / spectral acceleration (g) at bed rock level; M - moment magnitude of the earthquake; R - hypocentral distance and ε - standard error associated with the predicted values. The PHA value "z" is assumed to follow a normal distribution and this can be calculated as:

$$z = \frac{\ln PHA - \overline{\ln PHA}}{\sigma_{\ln PHA}} \qquad (4)$$

Where PHA is the various targeted peak acceleration levels which will be exceeded. $\overline{\ln PHA}$ is the value calculated using attenuation relationship equation and $\sigma_{\ln PHA}$ is the uncertainty in the attenuation relation expressed by the standard deviation.

SITE RESPONSE

When the seismic waves travel through the overlying soil, the waves gets modified and this is known as site effects. For the evaluation of site effects, the site classification has to be done and it can be done based on surface geology, geomorpgology or geotechnical data. One of the widely followed site classification schemes is based on the average shear wave velocity in the top 30 m (V_s^{30}). The National Earthquake Hazard Reduction Program (NEHRP) recommends (The Building Seismic Safety Council (BSSC), 2001) six site classes based on V_s^{30} values. The shear wave velocity ranges for each site class are, site class A (V_s^{30} > 1.5 km/s), site class B (0.76 km/s < V_s^{30} ≤ 1.5 km/s), site class C (0.36 km/s < V_s^{30} ≤ 0.76 km/s) and site class D (0.18 km/s < V_s^{30} ≤ 0.36 km/s). Site class E consists of soil profile with more than 10 feet of clay which is having a plasticity index higher than 20 or water content higher than 40% and V_s^{30} < 180 m/s. Site class F consists of soils like highly sensitive clays, collapsible weakly-cemented soils etc. and these types of soils (site class E and F) require site specific evaluations.

The amplification factors for south India for different site classes can be evaluated based on the following equation (Raghu Kanth and Iyengar, 2007).

$$\ln F_s = a_1 y_{br} + a_2 + \ln \delta_s \qquad (5)$$

Where a_1 and a_2 are regression coefficients, y_{br} is the spectral acceleration at rock level and δ_s is the error term. The values of the regression coefficients a_1 and a_2 will vary for different site classes and for different time periods. These values were derived based on the statistical simulation of ground motions (Raghu Kanth and Iyengar, 2007) and they also take into account the nonlinear site response of the soils. The value of spectral acceleration at surface level for different site classes can be obtained from:

$$y_s = y_{br} F_s \qquad (6)$$

Where F_s is the amplification factor and y_s is the spectral acceleration at the ground surface for a given site class.

LIQUEFACTION POTENTIAL EVALUATION

i. Based on SPT Values

One of the first methods to evaluate the earthquake loading (Cyclic stress ratio, CSR) was suggested by Seed and Idriss (1971) in the "simplified method".

$$CSR = 0.65 \frac{a_{\max}}{g} \frac{\sigma_{vo}}{\sigma'_{vo}} \frac{r_d}{MSF} \qquad (7)$$

Where a_{max} is the peak ground acceleration (at surface level), σ_{vo} and σ'_{vo} are the total and effective over burden pressure, r_d is the depth reduction factor used to account for the flexibility of the soil and *MSF* is the magnitude scaling factor. The above relationship was developed for an earthquake of magnitude M_w – 7.5 and if the magnitude of earthquake is different from this, it is being taken care off by the *MSF*.

Lots of probabilistic methods are suggested for evaluation liquefaction potential based on SPT values and one of the first attempts was done by Liao et al. (1988). A recent and comprehensive work in this area was done by Cetin et al. (2004). The probability of liquefaction at any given location can be evaluated using the procedure suggested by Cetin et al. (2004).

$$\mathrm{P_L} = \Phi\left[-\frac{\begin{pmatrix}(N_1)_{60}(1+\theta_1 FC) - \theta_2 \ln CSR_{eq} \\ -\theta_3 \ln Mw - \theta_4(\ln(\sigma'_{v0}/P_a) + \theta_5 FC + \theta_6\end{pmatrix}}{\sigma_\varepsilon}\right] \qquad (8)$$

Where, *PL is the* probability of liquefaction; Φ is the standard normal cumulative distribution function; $(N_1)_{60}$ is the corrected N value; FC is the fineness content in percentage; CSR_{eq} is the cyclic stress ratio without MSF (from Eq. 1); Mw is the moment magnitude of earthquake σ'_{v0} is the effective vertical pressure at the given depth; Pa is the atmospheric pressure (in the same unit as σ'_{v0}); $\theta_1 - \theta_6$ are regression coefficients; σ_ε is the model uncertainty.

The evaluation of earthquake loading in liquefaction potential evaluation requires the quantification of the uncertainties in earthquake loading. All the available methods, either probabilistic or deterministic, use a single ground acceleration and earthquake magnitude. The results obtained from the PSHA analysis show that several magnitudes contribute towards the ground acceleration and their percentage of contribution varies. This is clear from a seismic hazard curves given in Fig. 3. From this figure it is clear that it won't be fair to come to the conclusion that a particular ground acceleration

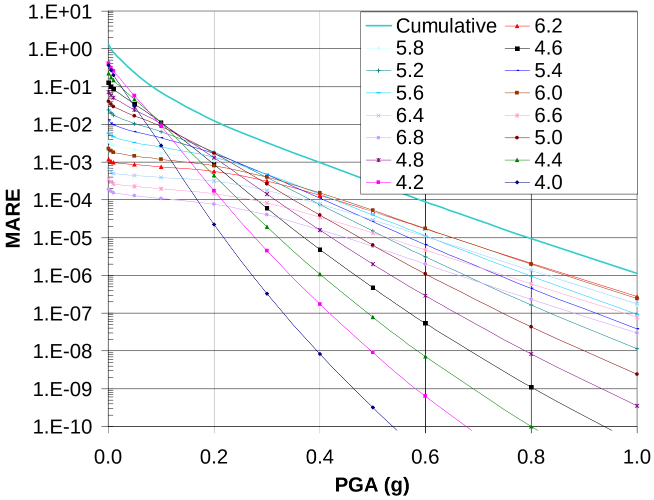

Fig. 3 The deaggregated seismic hazard curve at 17.3° N & 73.8° E

was produced by a certain magnitude, instead it is being contributed by different magnitudes. But the conventional liquefaction analysis methods fail to consider this aspect. More over the annual frequency of occurrence of lower acceleration values will be more and that of higher acceleration values will be less. The conventional liquefaction analysis fails to account for such variations in frequency of occurrence of ground motions also. Hence to account for these uncertainties in a better way, a probabilistic performance based approach was suggested by Kramer and Mayfield (2007). This approach was developed by modifying the probability of liquefaction evaluation suggested by Cetin et al. (2004).

$$\lambda_{EDP^*} = \sum_{i=1}^{N_{IM}} P\left[EDP > EDP^* \middle| \mathrm{IM} = \mathrm{im}_i \right] \Delta\lambda_{im_i} \qquad (9)$$

Where *EDP* – engineering design parameter like factor of safety etc.; EDP^* - a selected value of *EDP*; *IM* – intensity measure which is used to characterize the earthquake loading like peak ground acceleration, etc; im_i – the discretized value of *IM*; λ_{EDP^*} - mean annual rate of exceedance of EDP^*; $\Delta\lambda_{im_i}$ - incremental mean annual rate of exceedance of intensity measure *im*. The following equation can be derived by considering the *EDP* as SPT value and the intensity measure of ground motion as a combination of PGA and magnitude.

$$\lambda_{N^*_{req}} = \sum_{j=1}^{N_M} \sum_{i=1}^{N_a} P[\mathrm{N}_{\mathrm{req}} > \mathrm{N}^*_{\mathrm{req}} \mid \mathrm{a}_{\mathrm{i}}, m_j] \Delta\lambda_{a_i,m_j} \qquad (10)$$

Where $\lambda_{N^*_{req}}$ - annual rate at which corrected N_{req} value will be higher than $\mathrm{N}^*_{\mathrm{req}}$; N_{req} – corrected *N* value required to prevent liquefaction; $\mathrm{N}^*_{\mathrm{req}}$ - targeted values of corrected *N* values; N_M - number of magnitude increments; N_a - number of peak acceleration increments; $\Delta\lambda_{a_i,m_j}$ - incremental annual frequency of exceedance for acceleration a_i and magnitude m_j (this value is obtained from the deaggregated seismic hazard curves). The conditional probability in the previous equation can be written as

$$\mathrm{P}[\mathrm{N}_{\mathrm{req}} > \mathrm{N}^*_{\mathrm{req}} \mid \mathrm{a}_{\mathrm{i}}, m_j] = \Phi\left[-\frac{\begin{pmatrix} \mathrm{N}^*_{\mathrm{req}} - \theta_2 \ln(CSR_{eq,i}) - \theta_3 \ln(m_j) \\ -\theta_4 (\ln(\sigma'_{v0}/P_a) + \theta_6 \end{pmatrix}}{\sigma_\varepsilon} \right] \qquad (11)$$

The value of $\mathrm{N}^*_{\mathrm{req}}$ is the corrected *N* value (for both over burden pressure and percentage of fines, $N_{1,60,CS}$) required to prevent the liquefaction with an annual frequency of exceedance of $\lambda_{N^*_{req}}$.

Based on Eq. 10 and 11 curves showing the variation of annual frequency of exceedance with corrected SPT values can be drawn. From these curves the $N_{1,60,CS}$ values required to prevent liquefaction for any given return period can be determined. Such evaluation is not possible with any of the existing probabilistic or deterministic methods. Moreover by using this method it is possible to find the $N_{1,60,CS}$ values required to prevent liquefaction at any location without having the actual SPT values. Based on the site investigation, actual SPT values can be obtained and the factor of safety against liquefaction at that location can be calculated.

RESULTS AND DISCUSSIONS

Based on the analysis of the earthquake catalogue, the frequency magnitude relation obtained for the study is given below.

$$Log_{10} N = 4.67(\pm 0.4) - 0.9(\pm 0.07) M \qquad (12)$$

For calculating the seismic hazard values, the entire study area was divided into grids of size 0.1° x 0.1° (about 10000 grid cells) and the hazard values were calculated at the centre of each of these grids by considering all the seismic events and sources with in a radius of 300 km. While doing the seismic hazard analysis, the magnitude range and the hypocentral distance range were divided into small intervals. The range selected in magnitudes was 0.2 and that of the hypocentral distance was 5 km. The probabilistic seismic hazard analysis was done for each of the magnitude distance bins, and the peak horizontal acceleration (PHA) values were obtained at rock level. For the evaluation of liquefaction potential, the surface level PGA values were evaluated based on the assumption that the study area falls in site class D.

In order to consider the worst scenario for liquefaction, the water table was assumed to be at the ground level. The specific gravity of the soil was taken as 18 kN/m^3 and the SPT values required to prevent liquefaction was evaluated at a depth of 3 m. The liquefaction hazard curves were developed for each of the grid points, based on the methods explained in the previous sections. These curves show the variation of SPT values required to prevent liquefaction against the annual frequency of exceedance. The liquefaction hazard curves obtained for the selected cities in south India based on SPT values are shown in Fig. 4. From this figure the corrected SPT

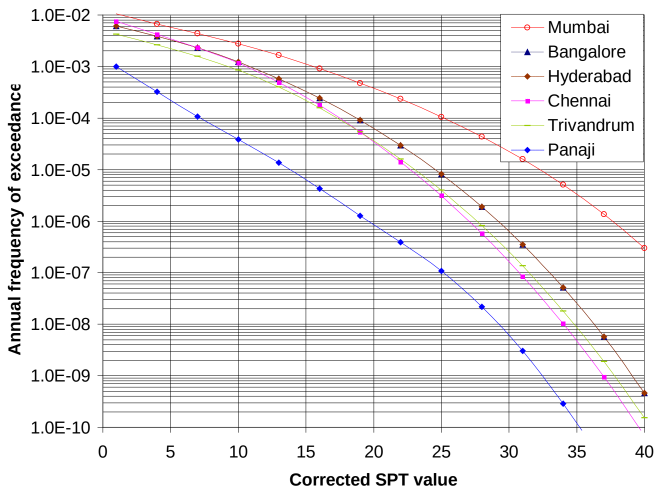

Fig. 4 Liquefaction hazard curves based on corrected 'N' values

value required to prevent liquefaction for any given return period can be obtained. The corrected SPT values required to prevent liquefaction for the selected cities with different probabilities of exceedance in 50 years are shown in Table 1. If the actual SPT values at the site (obtained from a site investigation) are higher than the values given in the table, then these locations are safe against liquefaction for that given return period. If not these sites are vulnerable to liquefaction hazard.

The SPT values required to prevent liquefaction for 10 % and 2 % probability of exceedance in 50 years were evaluated for a depth of 3 m. The contour curves showing the spatial variation of SPT values required to prevent liquefaction for return periods of 475 and 2500 years are given in Fig. 5 and 6. The highest corrected SPT value required to prevent liquefaction for a return period of 475 years is 23 at Koyna region. The SPT values required to prevent liquefaction for a return period of 2500 years is given in Fig. 6. The patterns of variation of these values are similar in both the figures. The values required for a return period of 2500 years is higher due to the increased return period. For any region in the study area, the factor of safety against liquefaction for a given return period can be obtained by dividing the values presented in this study with the actual SPT values obtained from site investigation (after correction). In a similar way liquefaction susceptibility maps can be prepared for different return periods and depths also. However these maps do not necessarily mean that the Koyna region is the most liquefaction susceptible area in south India. This can be ascertained only after getting the actual SPT data.

CONCLUSIONS

This paper explains the methodology for evaluation of liquefaction potential for a vast area based on SPT values. The entire process of liquefaction potential evaluation was done based on probabilistic methods and this will help in incorporating the uncertainties in earthquake loading in a

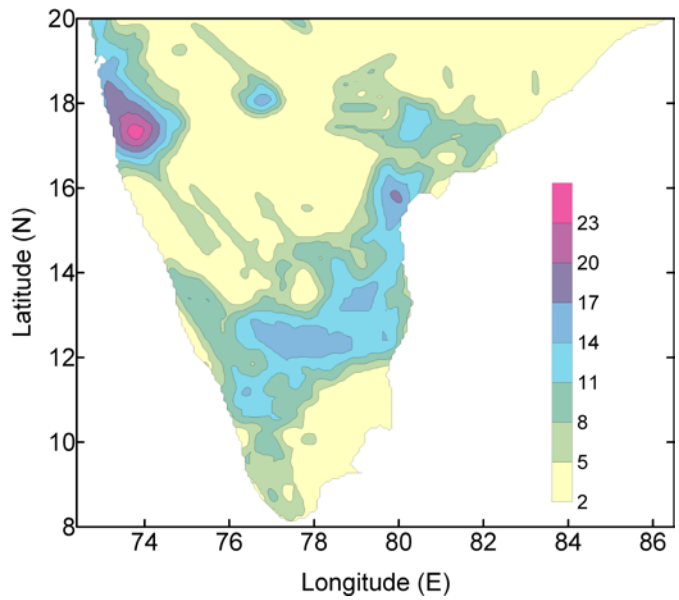

Fig. 5 Spatial variation of SPT values required to prevent liquefaction with 10 % probability of exceedance during 50 years (return period of 475 years)

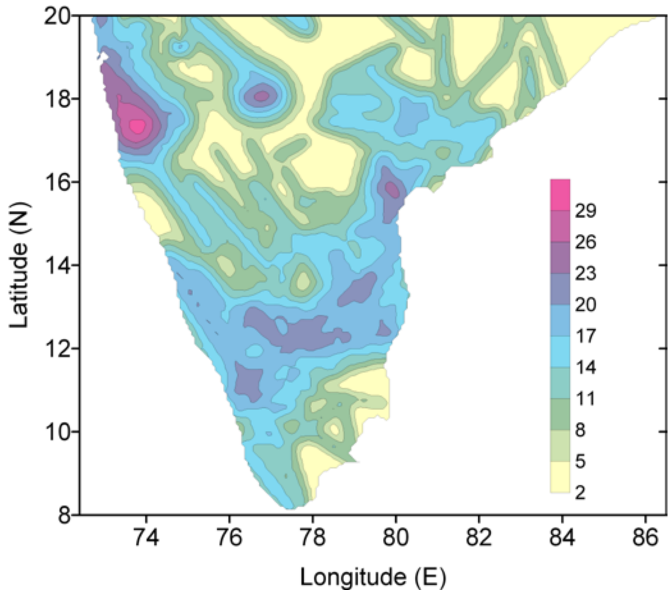

Fig. 6 Spatial variation of SPT values required to prevent liquefaction with 2 % probability of exceedance during 50 years (return period of 2500 years)

better manner. The performance based approach will give the parameters required to prevent the liquefaction for any given return period. In this work the liquefaction return period at a depth of 3m has been evaluated for return periods of 475 and 2500 years. However more research has to be done to come up with the return periods required for different types of structures. These maps will be very useful for identifying the liquefaction susceptible areas and taking remedial measures to reduce the hazard.

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REFERENCES

BSSC, [2001]. "*NEHRP recommended provisions for seismic regulations for new buildings and other structures 2000 edition, part 1: Provisions*", Report no. FEMA 368, Building seismic safety council for the federal emergency management agency, Washington, D.C., USA.

Cetin, K.O, Seed, R.B., Kiureghian, D.A., Tokimastu, K., Harder, L.F., Kayen, R.E. and Moss, R.E.S. [2004]. "*Standard penetration test-based probabilistic and deterministic assessment of seismic soil liquefaction potential*", J Geotech and Geoenviron Engg., 130(12), pp. 1314-1340.

Ganesha Raj, K. and Nijagunappa, R. [2004]. "*Major Lineaments of Karnataka State and their Relation to Seismicity - Remote Sensing Based Analysis*", J of the Geological Soc of India, Vol.63, pp. 430-439.

Gutenberg, B. and Richter, C.F. [1944]. "*Frequency of earthquakes in California*", Bull of the Seismo Soc of Am, 34, pp. 185-188.

Kramer, S. and Mayfield, R.T. [2007]. "*Return period of soil liquefaction*", J Geotech and Geoenviron Engg., 133(7), pp. 802 – 813.

Liao, S.S.C., Veneziano, D., and Whitman, R.V. [1988]. "*Regression models for evaluating liquefaction probability*", J. Geotech. Eng., 114(4), pp. 389–411.

Raghu Kanth, S.T.G., Iyengar, R.N., [2007]. "*Estimation of Seismic Spectral Acceleration in Peninsular India*", J Earth Sys Sci., 116(3), pp 199-214.

Regulatory Guide 1.165 [1997]. "*Identification and characterization of seismic sources and determination of safe shutdown earthquake ground motion*", Published by U.S. Nuclear Regulatory Commission.

SEISAT [2000]. "*Seismotectonic Atlas of India*", Geological Survey of India, New Delhi.

Seed, H.B. and Idriss, I.M. [1971]. "Simplified procedure for evaluating soil liquefaction potential", J Soil Mech and Found Engg., 97, pp. 1249-1273.