SEISMIC RESPONSE OF SOILS
A CASE STUDY OF SITE SPECIFIC GROUND RESPONSE ANALYSIS

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ABSTRACT: This paper presents the recent work carried out at Indian Institute of Science in the area of soil dynamics and earthquake geotechnical engineering. In the first part of the paper, a summary of work carried out on dynamic properties of Indian soils, liquefaction of sandy soils, pore pressure response in sandy soils subjected to cyclic loads is presented. The cyclic triaxial experiments on liquefiable sands from Bhuj, Ahmedabad and Assam regions have been carried out and the summary results are presented here. These regions experienced large scale liquefaction and site effects have been noticed during recent earthquakes. The data obtained for Bhuj, Ahmedabad and Assam sands, alightly deviate from the best-fit line in the plot of shear strain vs. number of cycles for initial liquefaction. The results fall closer to lower bound indicating lower cyclic strength of these sands for a given number of cycles for initial liquefaction when compared to global data. The dynamic properties such as shear modulus and damping ratios have been evaluated and summarised in this paper. In the second part of the paper, a case study of Bangalore where in site specific ground response analysis has been carried out based on large amount of SPT. Site amplification and microzonation maps of PGA at rock level and ground level have been developed and presented for Bangalore region. The study concludes that the Bangalore soils are moderately amplifying in nature and period of soil column varied from 0.08 to 4.5 seconds due to presence of silty sand and filled up soils.

1. INTRODUCTION

The seismic waves generated due to earthquakes developed vibrations in ground and create severe natural disasters. Earthquake ground motions exhibit the properties of a random process and, as such, generate complicated transient vibrations in structures. The response of such structures is essentially a function of the regional seismicity, the nature of the source mechanism, geology and local soil conditions. Case histories of earthquakes have shown that the intensity of a shock is directly related to the soil type and the soil stratification. Structures supported on rock and firm soil perform well compared to the structures built on soft and alluvium grounds. It has been demonstrated that the soft soil deposits undergo greater peak acceleration than the hard ground for the same input acceleration at bedrock level. The influence of actual soil condition is determined by a set of special studies of local conditions, which is useful in seismic microzoning. Microzoning takes into account the data of engineering and geological examination of the ground and also instrumented observations of seismic and strong motion responses, which will indicate the quantitative characteristics of ground shaking in an area into units of likely uniform ground response.

The extent and degree of damage during an earthquake is strongly influenced by the response of soil to ground shaking. But, the most important and commonly encountered problem in geotechnical earthquake engineering is the evaluation of ground response due to such shaking. Many investigators in the past, and more recently the geotechnical earthquake engineers have made attempts to develop quantitative methods for predicting the influence of soils on strong ground motion. In order to obtain the maximum benefit from many method of seismic analysis, an understanding of the dynamic response characteristics of materials becomes essential.

In this paper, experimental investigations were carried out using both stress and strain-controlled techniques on soil samples collected from earthquake affected areas such as Bhuj, Ahmedabad and Assam regions where extensive liquefaction and site effects have been noticed during recent earthquakes. A computerized cyclic triaxial testing facility with the options of both static and dynamic testing has been used. A few stress-controlled tests were also carried out on Bhuj sand to evaluate the liquefaction potential of these soils. The seismic responses in terms of, pore pressure generation, liquefaction potential, dynamic properties of these soils have been reported for a wide range of parameters.

2. MATERIALS TESTED

Figure 1 shows the ranges of grain size distribution for liquefaction susceptible soils proposed by Tsuchida (Iwasaki, 1986). Also shown in this figure is the grain size distribution of the soils from Bhuj, Ahmedabad and Assam for comparison purpose. This clearly highlights that the sands collected from these regions fall well with in the range of most liquefiable soils. Table 1 gives the summary of the index properties of the soil samples collected.

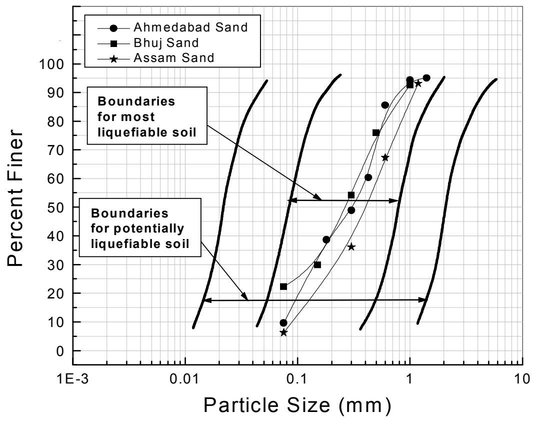

Fig. 1 Grain size distribution of soils used in this study along with soils tested along with soils susceptible for liquefaction proposed by Tsuchida (Iwasaki, 1986)

Table 1. Index Properties of soils

Index Property	Location of Soil Sample		
	Bhuj	Ahmedabad	Assam (Beltaghat)
Specific Gravity	2.67	2.66	2.66
Gravel (%)	NIL	NIL	NIL
Coarse Sand (%)	NIL	NIL	NIL
Medium sand (%)	35	37	48.8
Fine Sand (%)	43	53.4	45
Silt Size (%)	20	9.6	6.2
Clay size (%)	2	NIL	NIL
Liquid Limit (%)	21.6	NP	NP
Plasticity Index (%)	3.8	NP	NP
Max void ratio (e_{max})	0.68	0.67	0.91

3. PORE WATER PRESSURE GENERATION IN SANDY SOILS

Recent developments in studies of soil response to earthquake loadings have made it possible to incorporate the rates of pore water pressure build up in soils in to nonlinear response analyses of the grounds. Such pore pressure changes help in computing the changes in stress-strain behavior of soils in the deposit progressively as the earthquake progresses. The rate and magnitude of pore pressure generation in soils during seismic loading will have important effects on the shear strength, stability, and settlement characteristics of a soil mass, even if the soil does not liquefy.

Figure 2 illustrate the relationship between pore pressure ratio and number of cycles from the results of a test on Bhuj sand prepared at relative density of 8.9% and subjected to single amplitude cyclic shear strains (γ) of 0.18, 0.26 and 0.40% at an effective confining pressure of 100 kPa and frequency of 1 Hz. It is observed from the Fig. 2 that the increase of the pore pressure ratio up to the level of effective confining pressure is a function of both cyclic shear strain amplitude and number of cycles. For a given relative density and loading cycle, the rate of pore water pressure build up in sand increases with increase in the amplitude of cyclic shear strain. Similar trends in the relationship between pore pressure ratio and number of cycles can be observed when compared to the trends in Fig. 2.

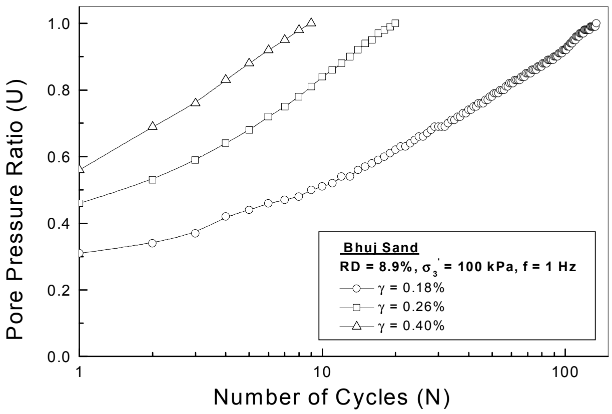

Fig. 2 Pore water pressure build up as a function of number of cycles for Bhuj sand for RD = 8.9% and various cyclic shear strains

While analyzing the series of relationship given in Figure 2, it has been found out that in case number of cycles (N) normalized by dividing it with NL which is the accumulative number of cycles required to build up excess pore water pressure to the level of effective confining pressure, there appears a tendency of establishment of a single relationship range independent of amplitude of cyclic shear strain (γ), relative density as shown in Figures 3 & 4 respectively. Dobry (1985) indicate that, despite a wide range of soils, relative densities, confining pressures and testing conditions a band can be developed for build up of pore water pressure as a function of cyclic shear strain amplitude as shown in Figure 5. Also shown in this Figure 5 is the data from the results of Bhuj, Ahmedabad and Assam sands for 10 cycles of loading. It is evident that the data of all these sands for ten cycles would plot with in the band of the results reported by Dobry (1985).

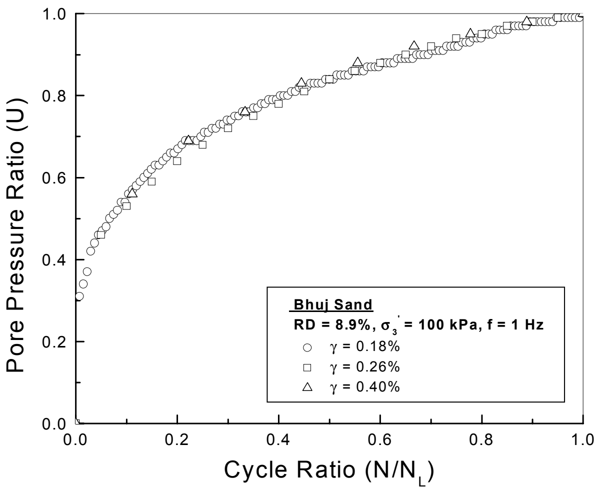

Fig. 3 Relationship between normalized pore pressure ratio and cycle ratio for Bhuj sand of RD = 8.9% and various shear strains

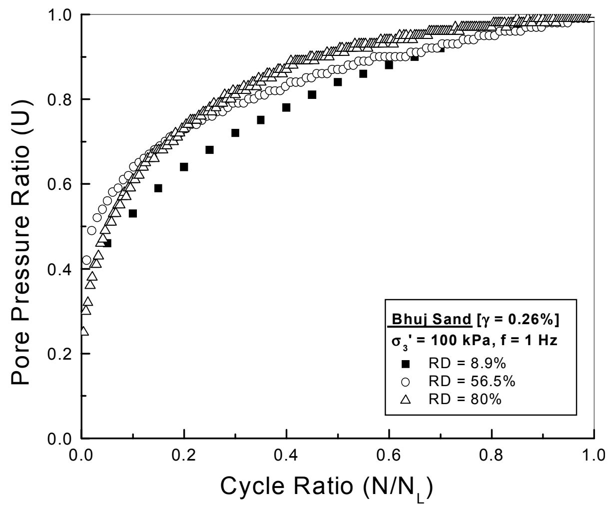

Fig. 4 Relationship between normalized pore pressure ratio and cycle ratio for Bhuj sand of RD =8.9, 56.5 & 80% and shear strain of 0.26%

Talaganov (1996) based on cyclic strain-controlled tests on dry and saturated sands reconstituted for a wide range of relative densities and confining pressures indicate the existence of a unique relationship between normalized pore pressures and normalized cycles for prediction of pore water pressure build up for all relative densities and confining pressures as shown in Figure 6. Also shown in this Figure 6 is the data from the results of Bhuj, Ahmedabad and Assam sands. It is clear that the data of all these sands for wide range of relative densities would plot with in the band proposed by Talaganov (1996).

4. LIQUEFACTION POTENTIAL OF SOILS

The high incidence of liquefaction during earthquakes, with its potential to damage, has made the liquefaction a prime subject of concern in geotechnical earthquake

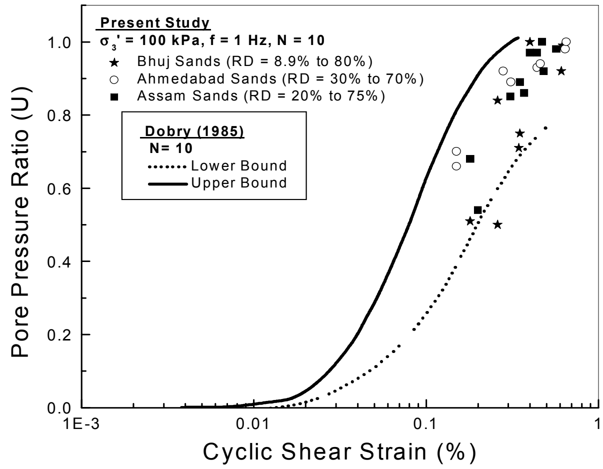

Fig. 5 Relationship between pore pressure ratio and cyclic shear strain for Bhuj, Ahmedabad and Assam sands

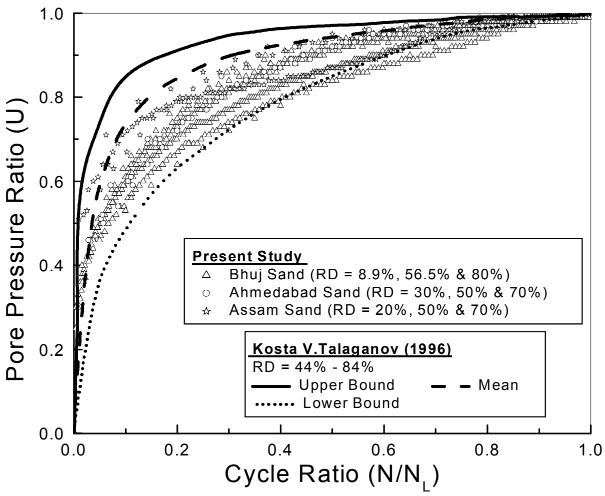

Fig. 6 Comparison of pore water pressure generation in Bhuj, Ahmedabad and Assam sands for different relative densities in strain-controlled tests

engineering. The occurrence of great earthquake (M = 8.7) in Assam, India during 1897 in the shillong plateau succeeded by three great earthquakes (1905, 1934 and 1950) in the adjoining Himalayan frontal arc, and recent Bhuj 2001 earthquakes indicate the vulnerability of these regions to large earthquakes and intense liquefaction soils. Recent research findings clearly indicate that sand deposited with significant silt content is much more liquefiable than clean sands (Yamamuro and Lade, 1998).

Figure 7 shows the cyclic resistance curves of the Bhuj sand tested at three different relative densities using stress-controlled technique. The cyclic strength of sand is specified in terms of the magnitude of cyclic stress ratio required to produce 5% double amplitude axial strain in 20 cycles of uniform load application (as described by Ishihara, 1993). The cyclic strengths obtained are 0.075, 0.09 and 0.182 for soil samples at relative densities 51%, 60% and 69.7% respectively. It is evident from the figure that the cyclic strength of sand increases as the relative density increases at a given confining pressure.

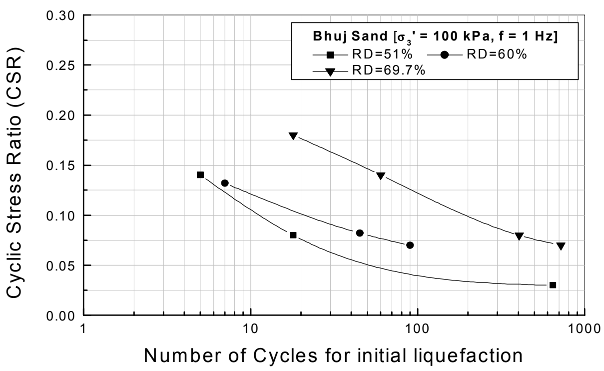

Fig. 7 Variation of cyclic stress ratio with number of cycles for initial liquefaction of Bhuj sand

Figure 8 shows the relationship between shear strain and number of cycles for initial liquefaction for Bhuj, Ahmedabad and Assam sands for a wide rage of relative densities, confining pressures and loading frequencies (0.2 Hz to 3 Hz) in strain-controlled tests. Also for comparison, shown in this figure is the relationship proposed by Talaganov (1996) emphasizing the existence of a unique relationship between shear strain and number of cycle for initial liquefaction for wide range of relative densities, confining pressures and frequencies. Despite wide scatter in the data, the results fall close to the best-fit curve. However, it is evident that most of the data obtained for Bhuj, Ahmedabad and Assam sands, deviate from the best-fit line and fall towards lower bound indicating lower cyclic strength of these sands for a given number of cycles for initial liquefaction.

5. DYNAMIC PROPERTIES OF SOILS

The analysis and design of a geotechnical engineering problem involving dynamic loading of soils and soil–structure interaction systems requires the determination of important parameters, the secant shear modulus (G) and the damping ratio (D) of the soils. It has been indicated that the shear moduli and damping properties of soils are strongly affected by the magnitude of shear strain amplitude especially for the range greater than the strain of 10^{-4}. On the other hand, shear strains induced in the soil deposits during strong earthquakes motions are estimated to be around 10^{-4} to 10^{-2}.

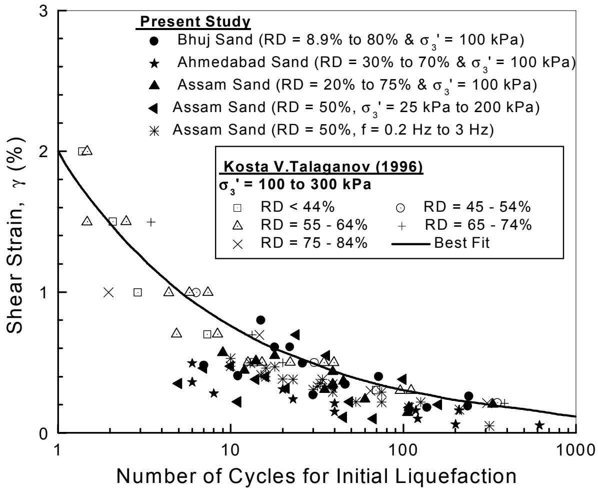

Fig. 8 Relationship between shear strain and number of cycles for initial liquefaction for Bhuj, Ahmedabad and Assam sands

Therefore it would be necessary to evaluate the strain-dependent dynamic properties of soils at shear strains of 10^{-4} to 10^{-2}. Figure 9 illustrate the variation of shear modulus of Bhuj, Ahmedabad and Assam sands covering a wide range of relative densities from 8.9% to 80% subjected to an effective confining pressure of 100 kPa and frequency of 1 Hz. In the range of shear strains beyond about 0.2%, there exists a narrow band of variation of shear modulus with the shear strains regardless of relative density of Bhuj, Ahmedabad and Assam sands.

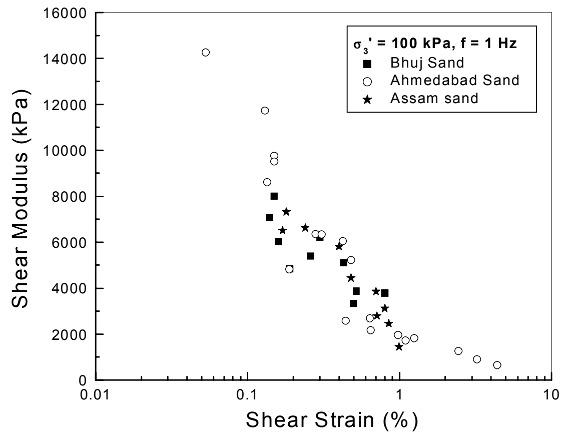

Fig. 9 Variation of Shear modulus and shear strain for Bhuj, Ahmedabad and Assam sand

The strain-dependent damping ratios of Bhuj, Ahmedabad and Assam sands are shown in Figure 10 for the same range of relative densities. It is evident from the plot that the damping ratios of all these sands show an increasing trend with shear strain without much scatter in the data.

This implies that the relative densities of soils do not significantly affect the damping ratios.

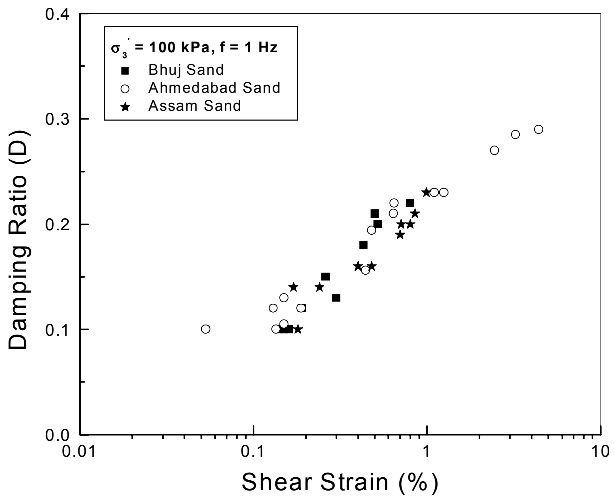

Fig. 10 Variation of Damping ratio and shear strain for Bhuj, Ahmedabad and Assam sand

6. LOCAL SITE EFFECTS IN BANGALORE

Site amplification refers to the phenomena wherein the local soils act as a filter and modify the ground motion characteristics. Amplification of seismic waves as they travel from bedrock to the ground surface causes transfer of large accelerations to structures hence causing destruction, particularly when the resulting seismic wave frequency matches with the resonant frequencies of the structures. Design of seismic resistant structures requires a good estimation of the site amplification during the expected earthquake and also the response spectrum at the ground surface. An attempt has been made to study site specific ground response analysis using SHAKE 2000 for Bangalore city.

Bangalore has experienced several minor earthquakes in the 20th century. There were more than 700 events of 3 to 3.9 magnitudes, about 150 events of 4 to 4.9 and about 25 events of 5 to 5.9 and 3 events around magnitude 6 reported in the study area of 350km radius around Bangalore city. The damage caused by these earthquakes was not large. The generally low background seismicity and the long repetition interval in this region often cause a false sense of security. Recent studies (Sitharam and Anbazhagan, 2006) highlight the presence of potentially active geological structures in the vicinity of Bangalore; one of them passes right through the IISc campus. Based on the available data, ground motions have been simulated and expected Peak Ground Accelerations (PGA) at rock depths were calculated in a 220 square km area of Bangalore. Bangalore has grown rapidly during the last 20 years. Many new buildings and colonies have been built on dry lake beds. What will happen to these buildings during a moderate earthquake? To ascertain these we need to identify sub-regions within Bangalore (essence of microzonation) that will then respond in a similar way to peak horizontal acceleration induced by an earthquake.

An attempt has been made to generated amplification, peak ground acceleration (PGA), periods of soil column and spectral acceleration maps of Bangalore based on analysis of data collated from 950 boreholes drilled in various parts of the city. PGA at ground level has been estimated from the borehole data and by carrying out one-dimensional site-specific ground response analysis. Acceleration time history at the ground surface and the response spectra have been generated and presented (Divya, 2006). This is further confirmed by recording the ambient noise for a selected period of duration at several locations in Bangalore city. The response spectrum is necessary to evaluate dynamic forces induced in structures. The microzonation map prepared using these outputs indicate varied amplification potential for Bangalore region. A peculiar feature of Bangalore region, falling in zone II in the seismic zoning map has the vast portion of reclaimed land by silted up encroaches into ponds giving rise to significant variation in ground response.

6.1 Input Ground Motion

Due to lack of strong motion data in the study area, it is necessary to generate synthetic earthquake data. Sitharam and Anbazhagan (2006) have identified Mandya-Channapatna-Bangalore lineament as the most vulnerable source for Bangalore and have reported that the MCE for this region has a moment magnitude of 5.1 thus developing a PGA of 0.146g at rock level. They have also simulated synthetic strong motion data by considering regional seismological factors and using SMSIM- Fortran Program for simulating ground motions developed by Boore (1983). The input rock motions at bed rock were generated for each considering the hypocentral distance from each bore log to the Mandya-Channapatna-Bangalore lineament. The acceleration-time data is then converted to SHAKE compatible format and given as input motion. The input motion for the location of the borehole number EW-18 is shown in Figure 11 and the map showing variation of peak acceleration at bed rock in Bangalore is shown in Figure 12.

6.2 Ground Response Analysis

The rock motion obtained from synthetic ground motion model is assigned at the bedrock level as input to obtain the peak acceleration values and acceleration time histories at the top of each sub layer for all the soil profiles. Response spectra at the top of the bedrock and at ground surface and amplification spectrum between the

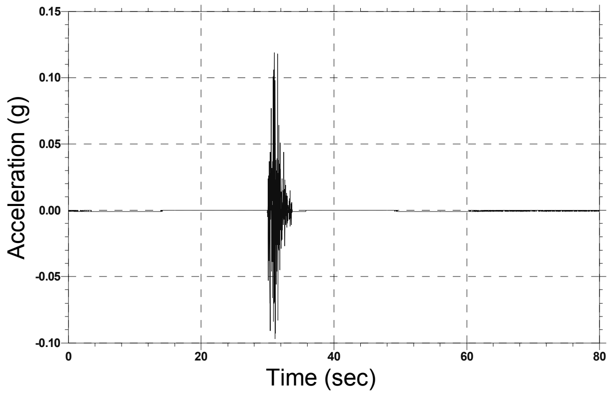

Fig. 11 Input motion at Bed Rock Level for Borehole Location EW-18

first and last layer at a frequency step of 0.125 are obtained at all the locations. Typical results obtained for borehole location EW-18 are illustrated in Figures 13a and b. Figure 13 (a) shows the acceleration time history at the ground surface.

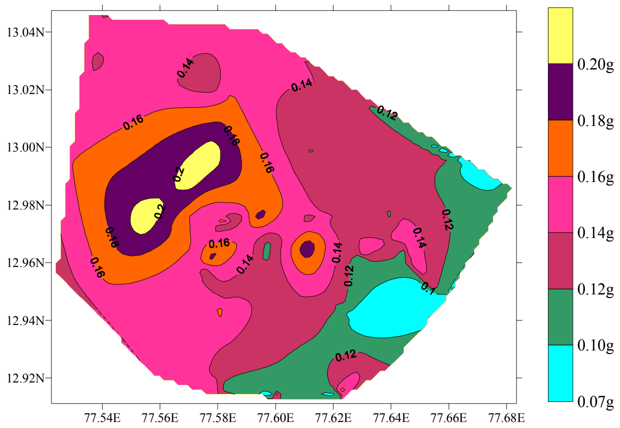

Fig. 12 Peak Acceleration Map at Rock Level

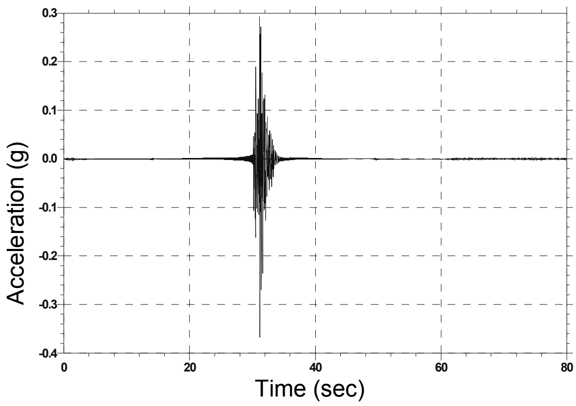

Fig. 13(a) Acceleration time history at ground surface

A comparison of Figures 11 and 13 (a) shows that the peak acceleration increases from 0.119g to 0.368g as the seismic waves travel through an overburden thickness of 15m. The variation of peak acceleration with depth is shown in Figure 13 (b).

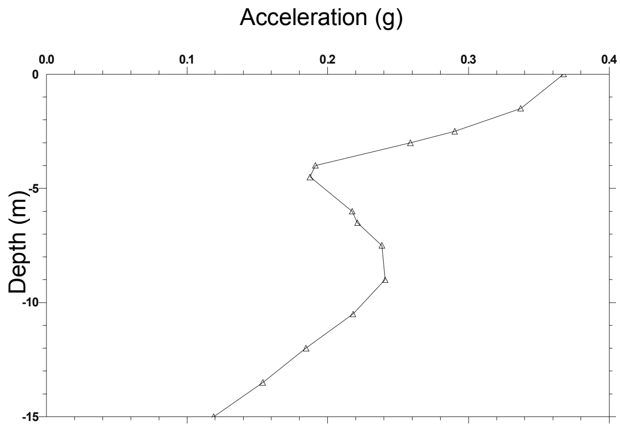

Fig. 13(b) Variation of peak acceleration with depth

6.3 Peak Ground Acceleration

The Peak Horizontal Acceleration (PHA) values at bedrock level are amplified based on the soil profile at various locations. The acceleration-time histories at various depths are obtained as output from SHAKE analysis. The peak acceleration value at the ground surface obtained for each location is plotted to obtain the Peak Ground Acceleration (PGA) map as shown in Figure 14. This PGA value ranges from 0.088g to 0.727g and is unevenly distributed due to variation in the soil profile at various locations.

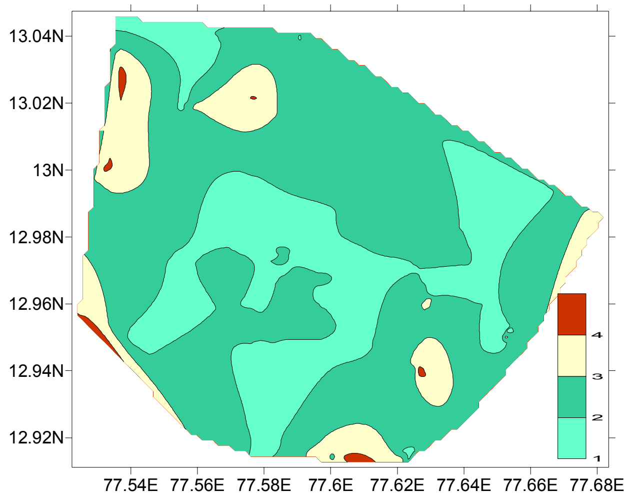

Fig. 14 Amplification Map of Bangalore

6.4 Amplification Factor

Ground motions with high peak accelerations are usually more destructive than motions with lower peak accelerations thus indicating that regions in the zone having PGA greater than 0.66g are seismically more unstable than the other regions. However, very high PGA's that last only for a very short period of time and have very high frequencies may cause little damage to many types of structures. Hence a better estimate of the regions of high seismic vulnerability can be made by identifying regions susceptible to higher amplification of the bedrock motion. The term "Amplification Factor" is hence used here to refer to the ratio of the peak horizontal acceleration at the ground surface to the peak horizontal acceleration at the bedrock. This factor is evaluated for all the boreholes using the PHA at bedrock obtained from the synthetic acceleration time history for each borehole and the peak ground surface acceleration obtained as a result of ground response analysis using SHAKE 2000. The amplification factor thus calculated ranged from 1 to 5.8. Lower amplification values indicate lesser amplification potential and hence lesser seismic hazard. The amplification factor map for Bangalore City is shown in Figure 15. It can be observed that the amplification factor for most of Bangalore region is in the range of 2-3. This is in agreement with Sitharam et.al. (2005) who have also concluded that most of Bangalore region has a moderate amplification potential.

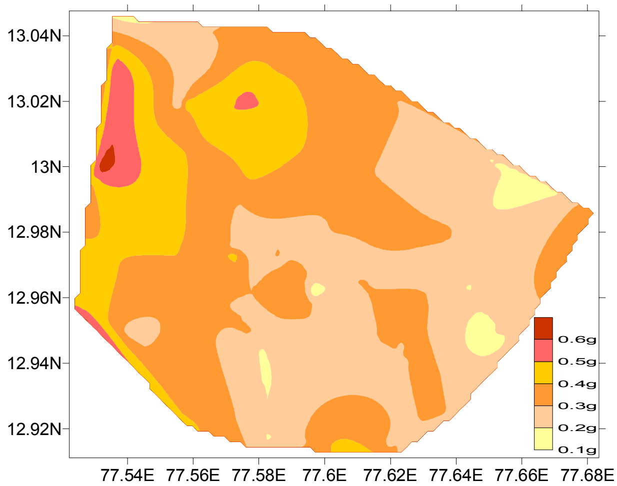

Fig. 15 Peak Ground Acceleration Map at Ground Level of Bangalore

6.5 Period of soil column

Results obtained from the site specific ground response analysis show that the natural periods of the analyzed deposits are in between 0.01sec and 0.45sec with about 85% of the locations having a period below 0.2sec. Figure 16 shows the variation of the period of soil column at various locations. However, the surface accelerations are high in many locations (refer Figure 9). This result is attributed to the characteristics of the frequency content of the accelerograms generated. The frequency content of a real event can be different from the frequency content of the synthetic accelerogram at various locations used in this study, even if the real event has the same parameters of the synthetic ground motion data used.

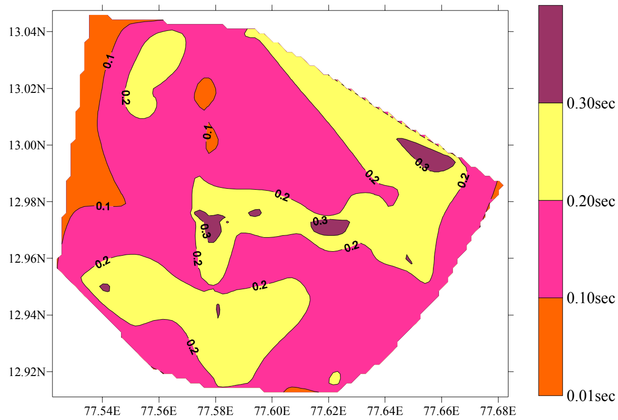

Fig. 16 Variation of period of the soil column at various locations

6.6 Response Spectra at ground surface

The frequency content of an earthquake motion will strongly influence the effects of that motion and hence only the PGA value cannot characterize the ground surface motion. A response spectrum is used extensively in earthquake engineering practice to indicate the frequency content of an earthquake motion. A Response Spectrum describes the maximum response of a single-degree-of-freedom (SDOF) system to a particular input motion as a function of the natural frequency/period and damping ratio of the SDOF system. It represents in a single graph the combined influences of terrain acceleration amplitudes and frequency components of the movement. Since the time history of the seismic excitement in a certain site is characterized by the corresponding response spectrum, the differences among the time histories of the movements at different places can be analyzed by the comparison of their response spectra.

The acceleration-time histories at various depths are obtained as a result of ground response analysis and these motions can be characterized by the corresponding response spectra. The ground surface response spectra for all the 125 borehole locations were plotted with 5% critical damping value, which is a pertinent value from the point of view of structural engineering. The spectral acceleration (SA) values for all the locations at 1.5 Hz, 3 Hz, 8 Hz and 10 Hz are computed.. The above frequencies were selected as they represent the range of natural frequencies of tall buildings to 1 storey buildings (Day, 2001; Govinda Raju et.al, 2004) and are hence ideal for all kinds of construction existing in the city.

At 1.5 Hz frequency, the SA values are very low and varied from 0.01g to 0.07g for all the locations. The SA map at 1.5 Hz frequency shows that there is not much variation of SA values and most of the area in the city has a SA value between 0.02g to 0.04g at this frequency. A spectral acceleration at 1.5 Hz is shown in Figure 17.

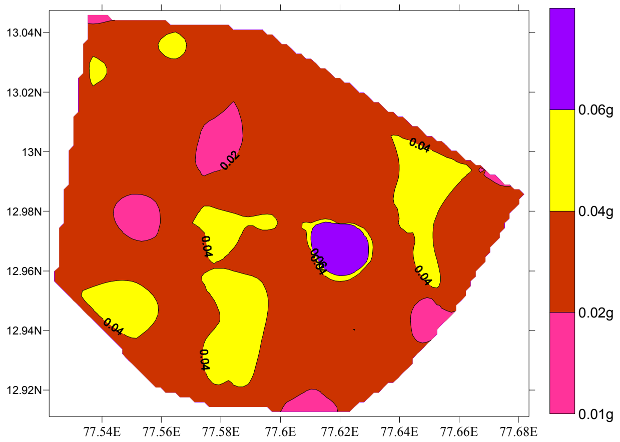

Fig. 17 Spectral Acceleration Map of Bangalore at 1.5 Hz Frequency

7. CONCLUSION

The soil samples collected from earthquake affected areas such as Bhuj, Ahmedabad and Assam regions, where extensive liquefaction and site effects have been noticed during recent earthquakes, have been tested using both stress and strain controlled techniques. The effect of different parameter such as Relative density, confining pressure, loading magnitude and frequency of cyclic load on the pore pressure, liquefaction potential and dynamic properties has been studied using reconstituted soil samples from those areas.

The bedrock motion and the soil profile details were considered as input and site specific ground response analysis was done for 125 locations in Bangalore using SHAKE 2000. The acceleration time history at the ground surface is obtained as output and was characterized by the PGA and the response spectra. The PGA at ground surface varied from 0.088g to 0.727g. The high value of surface accelerations at some locations may be due to the frequency of the base motions coinciding with that of the fundamental frequency of the soil column. The amplification factor which is a measure of amplification potential of the soil column was computed using this PGA and the peak acceleration at rock level. The range of amplification factor was 1.022 to 5.817. The high amplification factor at some locations is due to the presence of filled up soils, shallow water table depths and low SPT values which results in low average shear wave velocities. Thus, amplification of seismic waves depends not only on overburden thickness but also on various other factors like the frequency of the input motion, average shear wave velocity of the soil profile and water table depth. The results are reported as amplification factor map indicating zones of high vulnerability. The regions in zones I and II are seismically more stable than the regions in zones III and IV. Most of the area in Bangalore lies in zone II. Results obtained from the ground response analysis show that the natural periods of the analyzed deposits are in between 0.01sec and 0.45sec with about 85% of the locations having a period below 0.2sec. The response spectra for 5% damping at the ground surface obtained for all the borehole locations clearly indicate that the range of spectral acceleration at different frequencies varied over a wide range. At 5% damping, the range of SA at 1.5 Hz frequency was 0.01 g to 0.07 g, at 3 Hz frequency it was in the range of 0.03 g to 0.65 g, while at 5 Hz frequency it was in the range of 0.08 g to 1.14g.High value of surface accelerations estimated at some locations is on account of fundamental frequency of the soil columns coinciding with the frequency of earthquake motions.

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REFERENCES

Boore, D. M (2003), *Simulation of ground motion using the stochastic method*, Pure and Applied Geophysics, 160, 635-675.

Destegul Umut, (2004), *“Sensitivity Analysis of Soil Site Response Modelling in Seismic Microzonation for Lalitpur, Nepal,”* M.Sc Thesis, International Institute of Geo-Information Science and Earth Observations, Enschede, Netherlands.

Govinda Raju, L., Ramana, G. V., Hanumantha Rao, C. and Sitharam, T. G., (2004), *“Site-specific Ground Response Analysis,”* Current Science, Volume. 87, No. 10, pp.1354-1362. 15.

Sitharam, T. G. and Anbazhagan, P., (2006), *“Seismic Hazard Analysis for Bangalore Region,”* Journal of Natural Hazards, (in press)

Sitharam, T. G., Anbazhagan, P., Mahesh, G. U., Bharathi, K. and Nischala Reddy, P., (2005), *“Seismic Hazard Studies using Geotechnical Borehole Data and GIS,”* Symposium on Seismic Hazard Analysis and Microzonation, September 23-24, 2005, Roorkee.