Seismic Site Classification and Ground Response Analysis of Amaravati Region, Andhra Pradesh, India

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Abstract
Several devastations caused due to the earthquakes among other natural hazards and the local site conditions have a predominant influence on site amplification during the earthquake. The travel-time of average S-wave or shear wave velocity (Vs) to top 30 meters (V_s^{30}) depth from the surface level is an extensively used parameter to predict the local site potential for amplification during the earthquakes. In the present study, the Vs profile was developed for the Amaravati region and the site has been classified according to the NEHRP and Eurocode 8. The response of the ground is characterized through equivalent linear ground response analysis using DEEPSOIL with four different input motions to mimic earthquake hazard scenarios in this region.

The response spectra analysis was carried out to the soil profile of the average minimum V_s^{30}. Peak Ground Acceleration (PGA) obtained at the free field using all selected input motions and the values of PGA are varying from 0.27 g to 0.29 g. The spatial variation of amplitude and response spectra has been observed between the free field and rock outcrop motion. Based on the V_s^{30} profile, the region has been classified as class "D" according to NEHRP site classification and ground-type "C" by EC-8.

Keywords: Shear Wave Velocity (Vs), Seismic Site Classification, Standard Penetration Test (SPT), Peak Ground Acceleration (PGA), Ground Response Analysis (GRA).

Introduction
Southern parts of India have been considered as one of the stable continental regions over the few decades and the region was classified as a medium to moderate risk zone according to the building code of Bureau of India standards (BIS)[19]. But one of the most recent huge earthquakes i.e. Bhuj (2001, 7.7 M_w) claimed massive damage to the infrastructure over the 300 km radial distance from the epicenter[35].

It has become strong evidence that ground amplification is the most important aspect to be considered during structural design for the safety of the structures and to prevent casualties due to the earthquakes[32]. The scale of damage from the earthquake can be estimated by characterizing the level of ground shaking, amplitude, frequency and duration[3]. The local soil effects play a crucial role in the response spectra of the particular region or site. Generally, the seismic waves travel several hundreds of kilometers from source to surface through rock and soil strata[31,32].

Therefore, the structures are to be designed to the force by rupture mechanism at the source between the nearest fault to the site of the interest, the rupture mechanism of the ground response is shown in figure 1. The soil layer and bedrock properties influence the ground motion and together change the frequency content concerning the duration[5]. Hence, it is very important to know local soil conditions including rock type and response spectra while designing the new structures because the response at the surface mainly depends on the frequency and amplitude at the bedrock level[31,33].

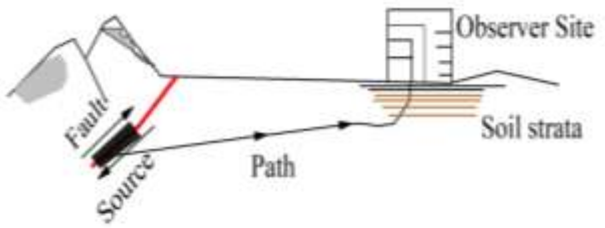

Figure 1: Mechanism of ground response

The Vs of the particular region is used to characterize the specific site conditions and this can be quantified by expressing the dynamic properties of various geological materials of the local site[15]. The principle of average time-travel of S-wave to the top 30 meters depth (V_s^{30}) from the ground surface is exclusively considered parameter to classify the site seismically according to many building codes worldwide.

According to the National Earthquake Hazard Reduction Program (NEHRP), the site has been classified into five different groups like class A, B, C, D and E based on the V_s^{30} profile of the particular region[10,24]. The range of V_s^{30} for class, A type site is greater than 1500 m/s and geologically the site has been classified as hard rock. Similarly, for a firm to hard rock type (site class B), the V_s^{30} ranging from 760 m/s to 1500 m/s, next to the dense soil and soft rock (site class C) type, the V_s^{30} is ranging from 360 m/s to 760 m/s, then for stiff soils (site class D) V_s^{30} is ranging from the lower level value of 180 m/s to a maximum of 360 m/s and finally, V_s^{30} less than 180 m/s sites are classified as type E with soft soil[10,27,30].

The propagation of Vs can be measured directly by conducting a cross-hole seismic test in two to three different boreholes and by a down or uphole test in a single borehole. The propagation of waves was also studied indirectly by using single processing equipment through two different surface methods of spectral analysis of surface waves and multichannel analysis of surface waves[34].

The V_s^{30} profile was considered by many building codes including American Society Civil Engineering (ASCE)[2], National Research Council Canada (NRCC)[27], Eurocode 8 (EC-8)[12] and Building Seismic Safety Council (BSSC)[10] to classify the site type. In addition to this, the V_s^{30} was also used to estimate the amplification factors in ground-motion prediction equations in the recent studies of Abrahamson et al[1]. But the evaluation of V_s^{30} for the top 30 meters is quite difficult and sometimes not possible to reach 30 meters depth due to the many constraints like environmental issues, budget and due to shallow rock depth. In these cases, the extrapolation technique is used to measure the near-surface shear wave velocities[28].

In the present study, the Vs were calculated based on the available correlation between Vs and SPT–N value. The relationship between the SPT-N value and Vs is derived by many researchers all over the world; the use of existing relationships is most commonly applied to obtain the Vs due to different constraints to conduct the precise test method[28]. In this study, seismic site classification and ground response analysis were carried out using 65 boreholes data from the Amaravati region (217.2sq.km).

Figure 2 shows the location map of the study area with the borehole locations. In practice, the ground response analysis is carried out based on the assumption that all extensive boundaries are horizontal and the response of the soil deposit is predominately caused by the horizontal plan moments[22,31].

The one dimensional (1D) response studies can be performed using Equivalent linear (EL), Non-linear (NL) analysis through different computer tools like SHAKE, DEEPSOIL, EERA and Pro-Shake. In recent days use of DEEPSOIL[16] is the most commonly preferred tool to study response analysis over the world. The response analysis through DEEPSOIL can be performed in equivalent linear and nonlinear by 1D and 2D conditions in frequency-domain and time-domain including with and without pore water pressure generation and with convolution and deconvolution[32].

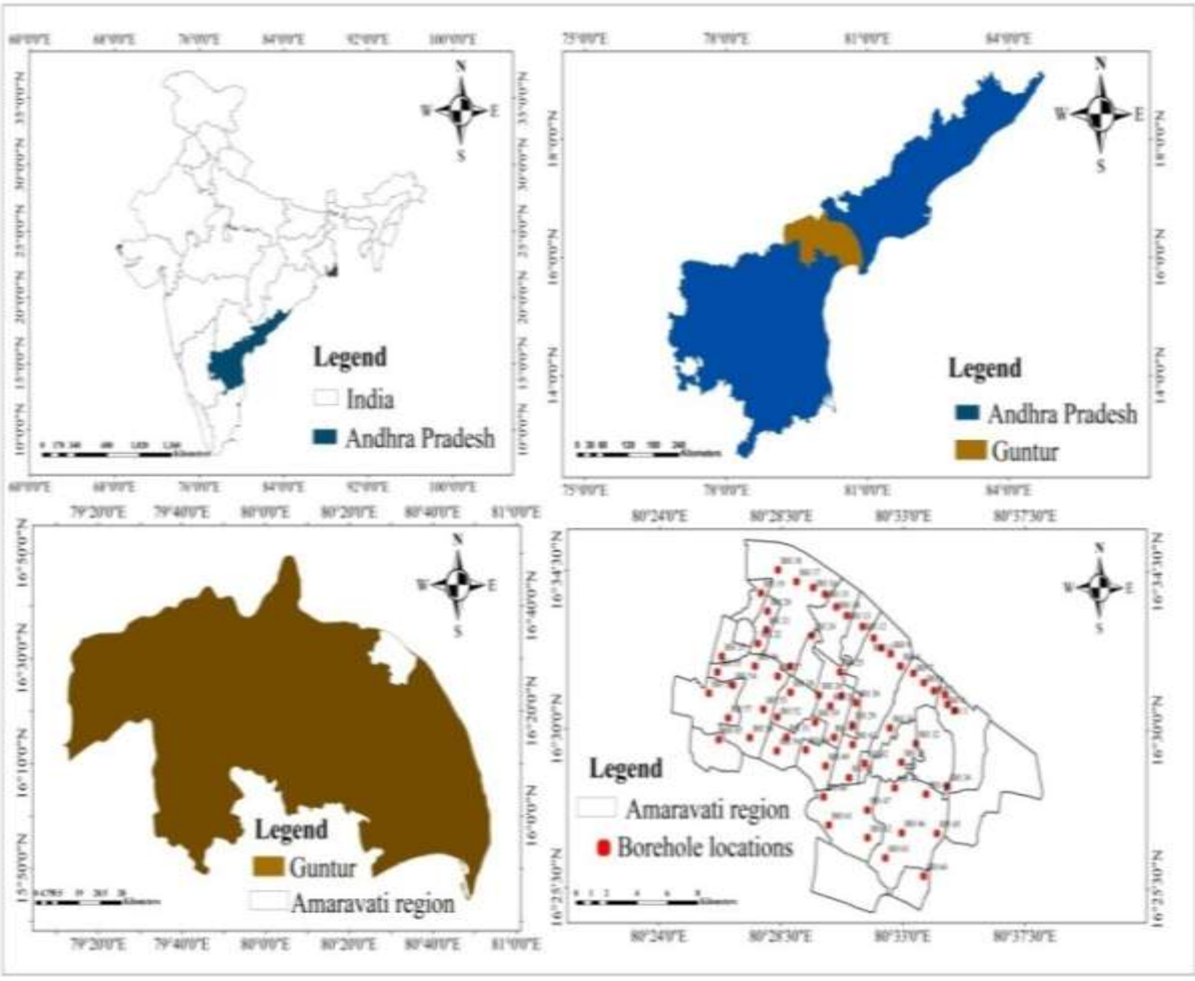

Figure 2: Location map of the study area with borehole locations

Seismic Site Classification: The site classification involves the measurement of the Vs at different locations. In this study, the Vs was calculated by using the existing empirical relation between the Vs and SPT-N values. The geotechnical investigation of layered is usually done by conducting *in situ* tests. The most commonly used *in situ* tests are SPT and cone penetration tests. The SPT test is one of the extensively preferred *in situ* tests and used to investigate the soil stratifications and to evaluate the various engineering properties (Permeability, compressibility and shear strength) of cohesionless and relatively stiff soils[14].

On the other side, the cone penetration test is preferred in the case of soft soil deposits. In this study, SPT-N values are collected at every 2 meters of regular intervals from different locations of the study area (fig.1). The SPT-N values are measured (according to BIS) [20] from the boreholes of 150 mm diameter by advancing the shell into a desirable depth using auger boring with the split spoon sampler. The number of hammer blows required to penetrate every 150 mm depth is recorded with the 63.5 kg hammer falling from the height of 750 mm.

Due to the presence of loose material up to several meters depth, the number of blows for the first 150 mm drive is ignored. The cumulative number of blows required to penetrate the next 300 mm depth is termed as SPT value or N value. From the bore log information, the soil is classified as per the BIS[18].

The majority of soil types observed in the Amaravati region are CH (Inorganic clays) MH (Inorganic silts), SC (clayey sands), SM (silty sand), SP (fine sand), CI (Inorganic clay)[35].

Correlation between Vs and N value: To calculate the Vs with SPT- N value, many researchers all over the world developed a correlation between the Vs and N value for different soils and also for all soils separately[28]. In this study, few correlations (for all soils) were developed by the researchers like Hanumantha Rao et al[15] for Delhi, Uma Maheswari et al[25] for Chennai, Anbazhagan et al[4] for Bangalore, Naik et al[26] for Kanpur and Kirar et al[21] for Roorkee have been used to calculate the Vs. The Vs values of the present study have been compared with the selected correlation as shown in figure 3.

From figure 3 it is observed that the correlation proposed by Kirar et al[21] for Roorkee is closely matching with the average Vs values. In further studies to calculate the Vs values, the Kirar et al[21] relation has been used.

Seismic microzonation includes the estimation of specific site amplification and scale of ground shaking followed by measurement of V_s^{30}. The Vs values are mostly considered by many building codes all over the world to classify the site seismically[30]. In many locations, the depth of the rock is very near to the surface, in this case, the Vs profile does not reach 30 meters depth[28,40].

Since the 30 meter average of Vs value is important to estimate the site amplification[30], many empirical studies were conducted using different data sets by various researchers like Boor et al[9], Bergamo et al[7], Dikmen[11], Imai and Yoshimura[17] and Ohsaki and Iwasaki[29] to estimate the Vs for near-surface shear wave velocity profile of the sites whose depth does not reach to 30 meters by extrapolation method. In the present study, a total of 65 bore logs data were collected from all the parts of the Amaravati region.

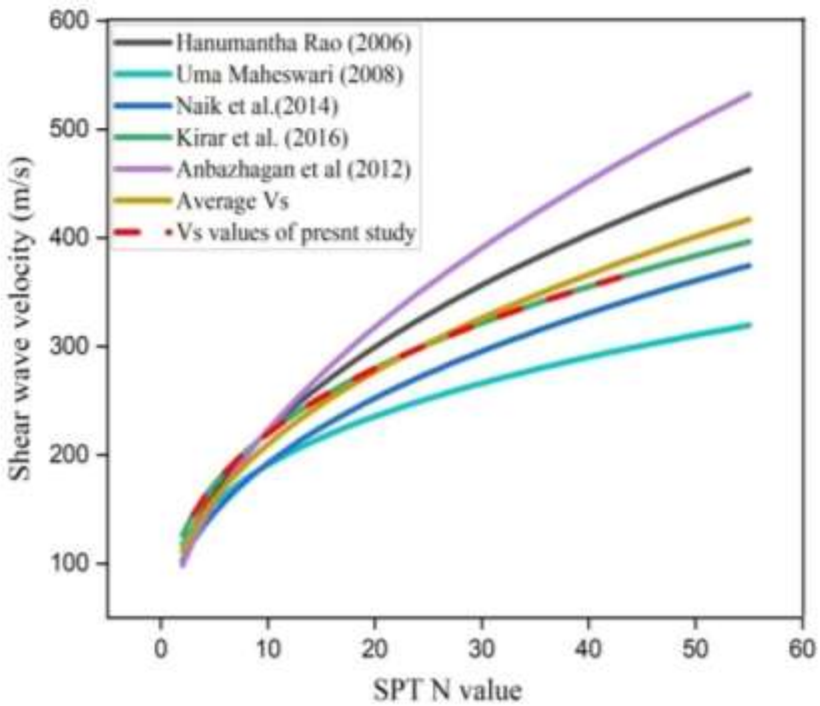

Figure 3: Comparison of average Vs (m/s) values with existing literature

The minimum depth of the bore log is 16 meters and the maximum is 45 meters. From the data set, it is observed that 50 percent of bore logs not reaching 30 meters required depth to calculate the Vs values. Hence, to calculate the Vs for 30 meters depth, the extrapolation method proposed by Boore[8] has been used. According to the Boore[8], if the velocity profile is available to depth (d), then to calculate the V_s^{30}, the following relation between the d and 30 meters can be used [8, 28,40].

$$V_s^{30} = \frac{30}{tt(d) + (30 - d)/V_{eff}} \qquad (1)$$

In equation 1, tt(d) is the travel time to reach a particular depth d and V_{eff} is the timed average to a depth of d. V_{eff} is the effective velocity from the depth d to 30 meters. The V_{eff} is calculated based on the simple assumption that the V_{eff} is equal to the velocity at the bottom of the soil profile. Hence, effective velocity is equal to $V_{eff} = V_s$ (d).

Finally, the Vs is calculated at 30 meters depth using Boore[8] relation for the boreholes of less than 30 meters in actual depth. Further, the Vs was calculated for all 65 bore logs using the Kirar et al[21] relations between the Vs and SPT-N value ($Vs=99.5*N^{0.345}$) for all locations. From the results, the average minimum Vs is 265.83 m/s, the maximum is 315.2 m/s and the average Vs of all bore logs is 288.01 m/s. All the Vs values are compared with the NEHRP (BSSC)[10] for site classification.

Therefore, the Amaravati region was classified as class D (stiff soil with Vs between 180 m/s to 360 m/s) and according to site class of NEHRP[10] and through EC-8[12], the region ground type comes under C (Deep deposits of dense and medium dense sand, gravel or stiff clay) with Vs between 180 m/s to 360 m/s and SPT-N value between 15-50. Hence, it is observed from the site classification that the site classified only one specific class. Hence the Vs profile for the Amaravati region developed average minimum Vs profile (i.e. Vs = 265.83 m/s) as shown in figure 4.

Ground Response Analysis: The scale of damage during the earthquake is purely based on the characteristics of a particular event and the interaction of site response to the vulnerability of the structures[36]. The pattern of vulnerability is influenced by the ground shaking during the earthquake. The geotechnical characteristics and subsurface characteristics of different soil deposits have a strong influence on ground shaking[38].

Therefore, the site effects strongly depend on the different parameters like amplitude, frequency and duration. Ground Response Analysis (GRA) was carried out for the soil profile of the average minimum V_s^{30} (i.e. 265.83 m/s) using 1-D equivalent linear analysis through DEEPSOIL[16] with four different input motions. The geotechnical classification of the selected soil profile for GRA is given in table 1.

Input Motion: To perform the specific site response analysis, the basic requirement and crucial component are the selection of acceleration time–histories of recorded data from the existing records. Many large earthquakes occurred in India but the recording of the actual ground motion started from the 1986 Dharmsala earthquake[23]. Due to the lack of recorded regional ground motion data for the specific region, the use of readily available stochastically simulated ground motions is very commonly obtained all over the world for site-specific response study[6].

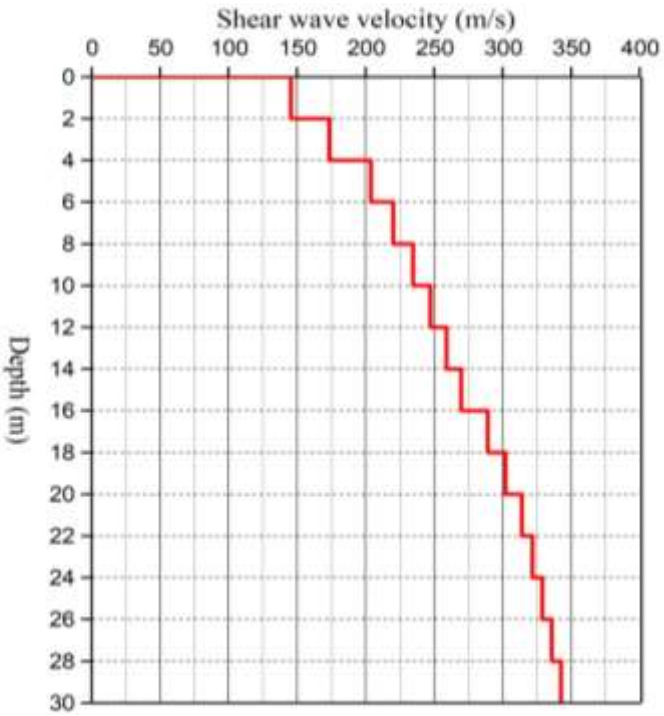

Figure 4: Shear wave velocity profile for Amaravati region

In this study, the GRA for the selected soil profile was carried out using four different input motions. The time histories of three input motions are collected from the COSMOS (Consortium of Organization for Strong Motion Observation System) database and the input motion (Northridge) selected from the panel of DEEPSOIL[16].

The details like name of the event, time of occurrence, place, magnitude and depth are given in table 2. Before using a particular input motion, the two different corrections are applied to the selected one. First, the base correction applied is to remove the records of time histories from other sources (e.g. Blasting), the base correction follows the step-time analysis in recording acceleration, then the next scaling is done to required g according to Hadley et al[13].

The time history plots were drawn between the acceleration and time for all input motion verse selected soil profile to zero period acceleration (after base correction and scaling to required g) starting from Bhuj, Chamba, Northridge and Uttarkashi as shown in figures from 5 to 8.

Results and Discussion

The GRA studies were performed for the Amaravati region through equivalent linear analysis using DEEPSOIL[16]. The site-specific response studies are widely used to estimate the amplification and response spectra of a particular site of layered soils.

The surface PGA estimated for the location of Vs minimum using four different input motions is shown in figures 5 to 8. The surface PGA varying from 0.27 g to 0.29 g and the amplification factor have been estimated for the same location using all input motions.

For evaluation of modulus of reduction and damping characteristics of the selected profile, the models suggested by the Vucetic and Dobry[39] were obtained for clayey soils based on the plasticity index. Seed et al[37] recommended curves used based on the Vs values at a different depth level from the inbuilt source of the DEEPSOIL[16].

Table 1
Geotechnical characteristics of the selected soil profile for GRA

Thickness range (m)	Soil type	Soil classification	SPT-N value	Vs (m/s)
00-2.00	Inorganic fine silty clayey soil	MH - CH	3	145.35
2.1 - 4.00	Inorganic fine silty clayey soil	MH - CH	5	173.37
4.1-6.00	Inorganic fine silty clayey soil	MH - CH	8	203.89
6.1-8.00	Inorganic fine silty clayey soil	MH - CH	10	220.20
8.1-10.00	Poorly graded silty sand and clayey sand	SC -SM	12	234.50
10.01-12.00	Poorly graded silty sand and clayey sand	SC - SM	14	247.31
12.01-14.00	Poorly graded silty sand and clayey sand	SC - SM	16	258.97
14-01-16.00	Poorly graded silty sand and clayey sand	SC -SM	18	269.71
16.01-18.00	Poorly graded silty sand and clayey sand	SC - SM	22	289.04
18.01-20.00	Poorly graded silty sand with gravelly sand	SM - SP	25	302.07
20.1-22.00	Poorly graded silty sand with gravelly sand	SM - SP	28	314.12
22.1-24.00	Poorly graded silty sand with gravelly sand	SM - SP	30	321.68
24.01-26.00	Poorly graded silty sand with gravelly sand	SM - SP	32	328.93
26.1-28.00	Poorly graded silty sand with gravelly sand	SM - SP	34	335.88
28.1-30.00	Inorganic clay with gravelly clayey soil	CI	36	342.57
31.01-34.0	Inorganic clay with gravelly clayey soil	CI	38	349.02
34.01-36.00	Gravelly sand with less or no fines	SP	40	355.25
36.01-38.00	Gravelly sand with less or no fines	SP	42	361.28
38.01-40.00	Gravelly sand with less or no fines	SP	43	364.22
40.01-42.00	Hard soil	HS	44	367.13
42.01-45.00	Hard soil	HS	46	372.80

Table 2
Details of selected input Time- Histories

Time History	Date of the event	Magnitude (M_w)	Depth (Km)	Latitude	Longitude	Recorded station	PGA (g)
Bhuj[31]	26-01-2001	7.7	16	23.42	70.23	Ahmedabad	0.1
Chamba*	24-03-1995	5.1	33	32.56	75.99	Chamba	0.14
Northridge[16]	17-01-1994	6.7	17.5	34.2	118.55	P0885	0.27
Uttarkashi[23]	19-10-1991	6.8	10	30.48	78.36	Bhatwari	0.25

* COSMOS

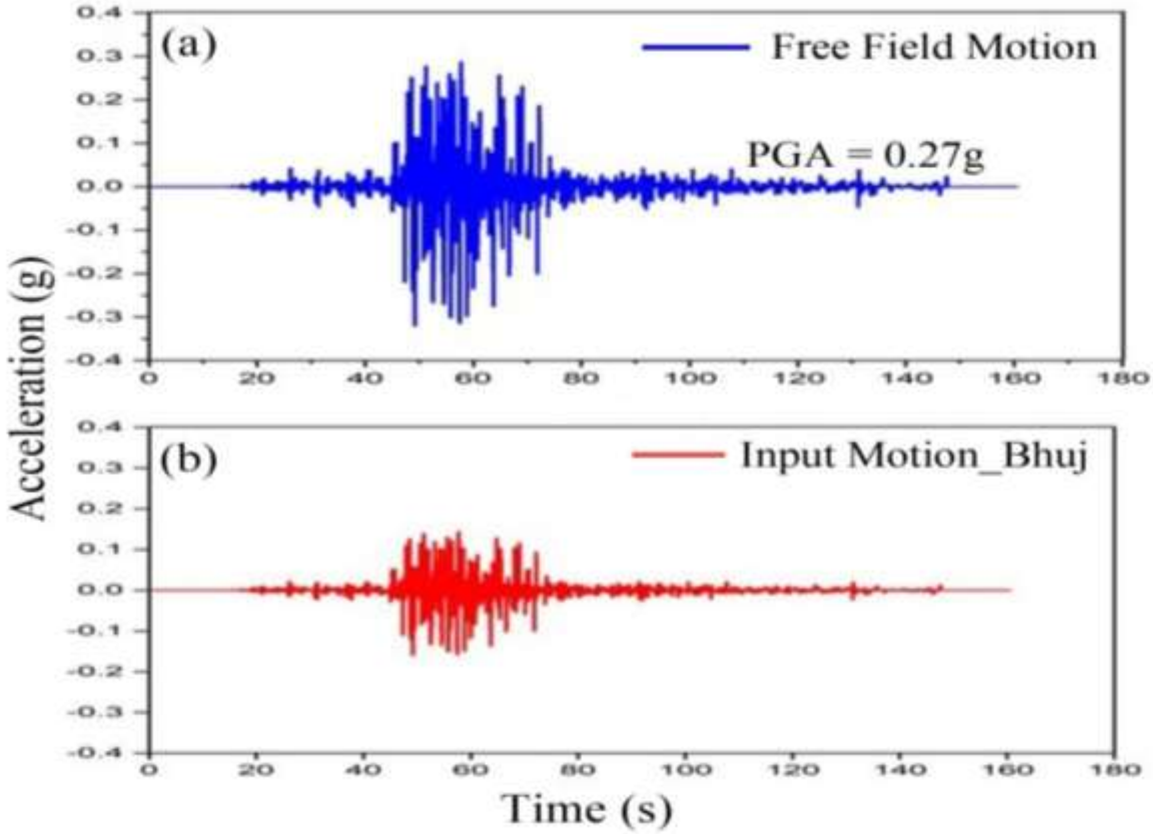

Figure 5: Acceleration time histories of a) Free field motion b) Input motion (Bhuj)

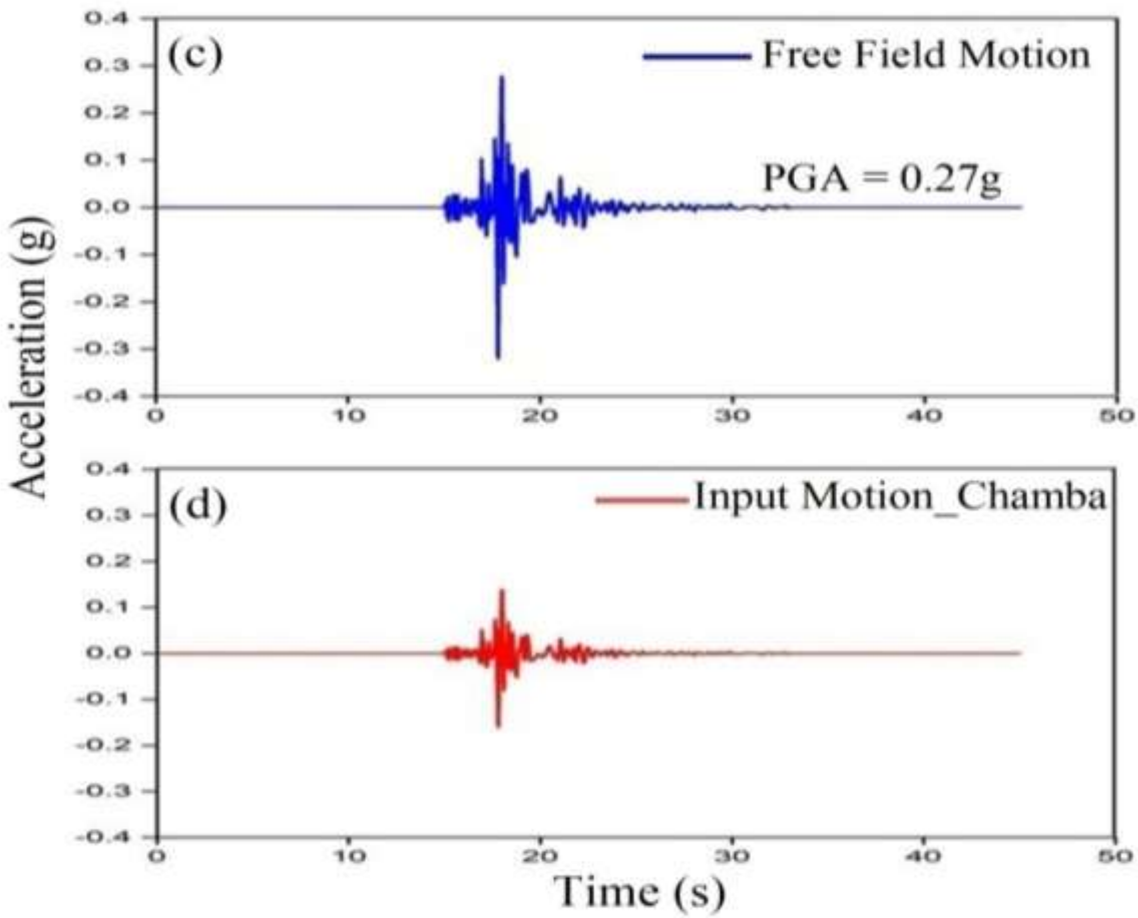

Figure 6: Acceleration time histories of C) Free field motion D) Input motion (Chamba)

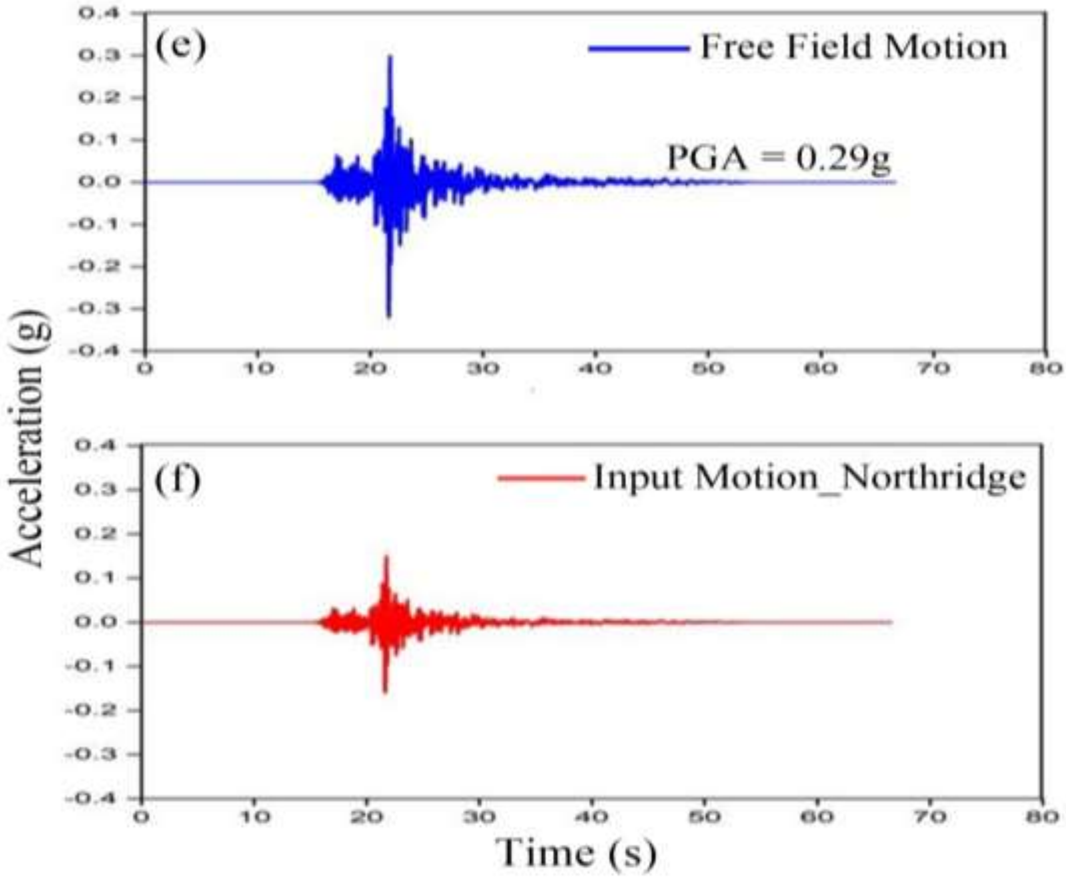

Figure 7: Acceleration time histories of e) Free field motion f) Input motion (Northridge)

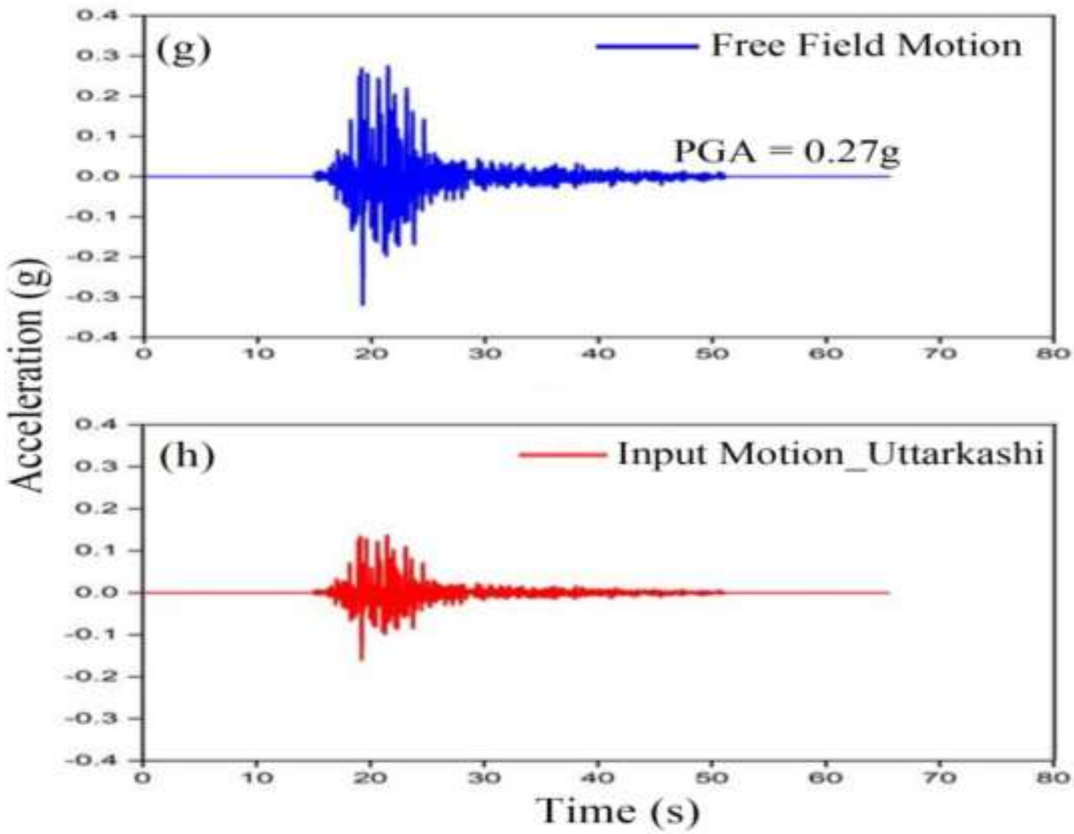

Figure 8: Acceleration time histories of g) Free field motion h) Input motion (Uttarkashi)

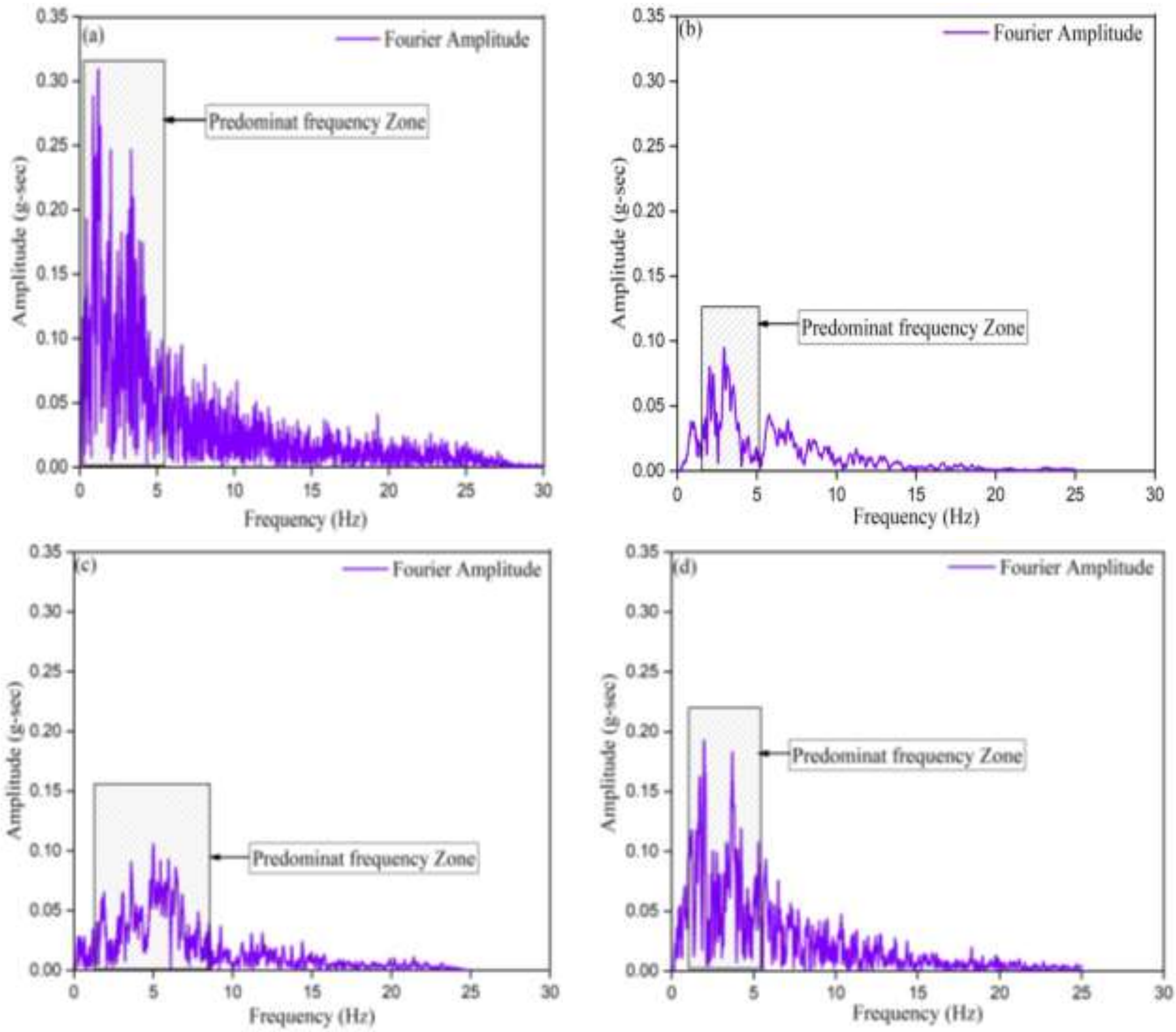

Figure 9 (a-d): Fourier amplitude for selected borehole using 4 different input motions a) Bhuj b) Chamba c) Northridge d) Uttarkashi

The frequency content of ground motion can be obtained from the Fourier transformation function (by transferring the time domain into the frequency domain). Figure 9(a-d) shows the Fourier amplitude spectrum to the selected soil profile for four different input motions. From figure 9, the surface level Predominate Frequency Zone (PFZ) is observed between the frequency of 0.2 Hz to 5.2 Hz using Bhuj input motion and similarly, from Chamba earthquake motion as an input, the PFZ is observed between 2.0 Hz to 4.4 Hz next from the Northridge input motion the PFZ varied from 1.7 Hz to 6.8 Hz and the PFZ is 0.09 Hz to 4.8 Hz from the Uttarkashi earthquake input motion.

The response spectrum plots were drawn for the selected soil profile to compare the response at free field level and rock outcrop for four considered input motions shown in figure 10 (a-d). The response spectrum results of any site are normally considered in structural design and used to obtain the suitable design for earthquake resistant structures. In this study, the normalized response spectra curves were drawn for the spectral period of 0 s to 4 s as shown in figure 11. According to the BIS code[19], the surface level response spectrum is compared with the spectral periods of medium soil and presented along with the response curves in figure 11.

Conclusion

In the current study, the GRA was carried out for the Amaravati region of Andhra Pradesh State of India. The detailed geotechnical characteristics of the study area were observed from the earlier studies of Reddy et al[35] and using SPT profiles at various locations. The Vs was calculated using the empirical correlation between the Vs and SPT-N value and for the short depth (i.e. less than 30 meters), the Vs was calculated based on the method proposed by Boore[8].

The regression coefficient (R) is 0.96 obtained for the Vs values and SPT N values using Kirar et al[21] relationship. The Vs values for an average of 30 meters are the most important parameters considered for seismic site classification according to many building codes.

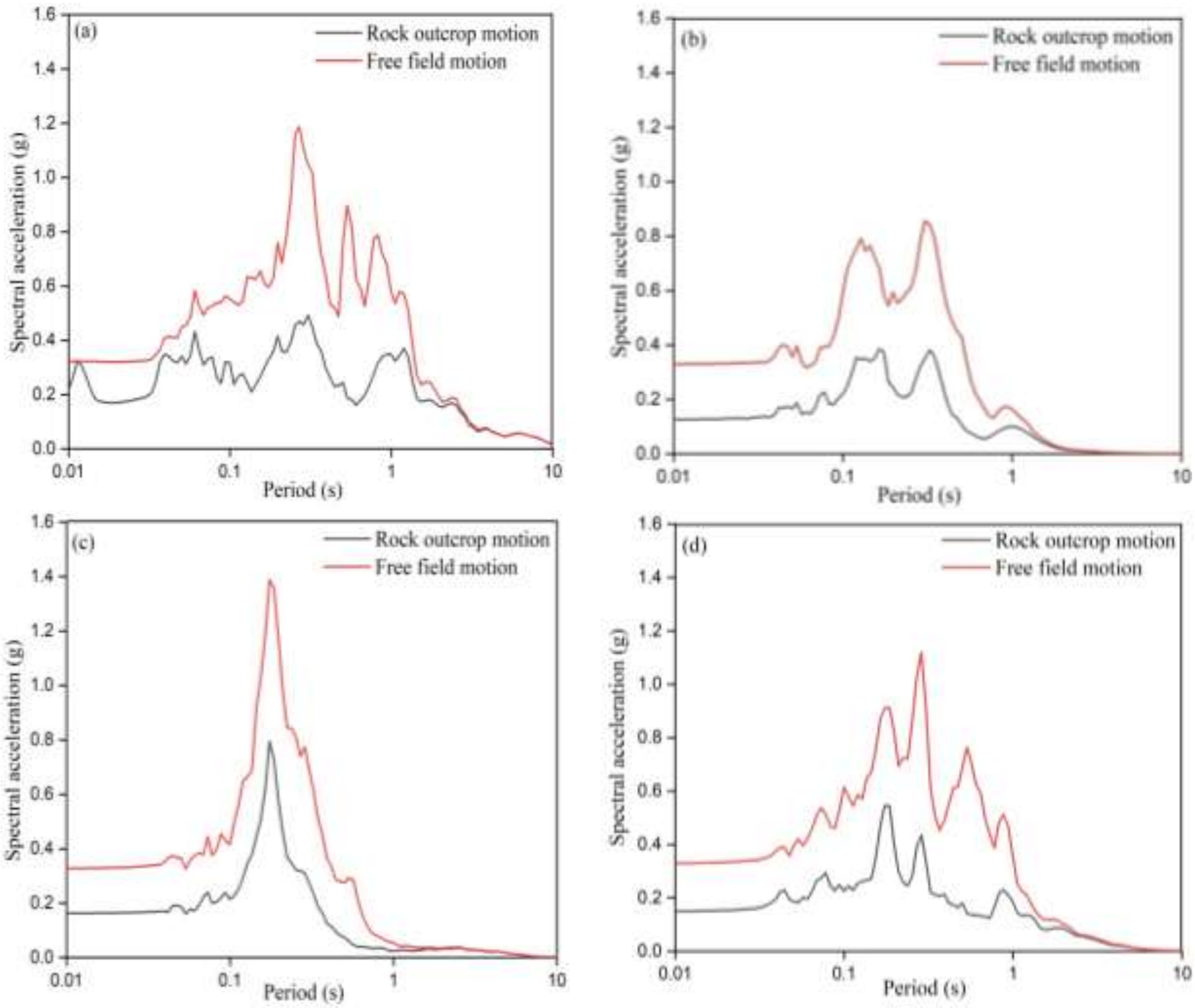

Figure 10 (a-d): Comparision of response spectra between rock outcrop and free field through all selected input motions a) Bhuj b) Chamba c) Northridge d) Uttarkashi

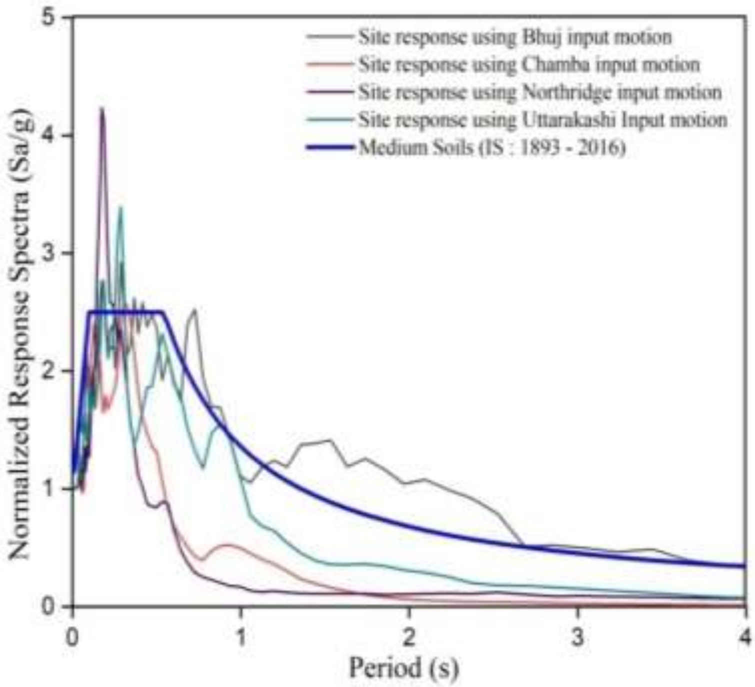

Figure 11: Normalized response spectra at a surface level using different input motions for MCE of IS code 1893

In the present study, the average Vs for 30 meters depth was calculated for all 65 borehole locations and based on the obtained Vs values, the site has been classified as class "D" according to NEHRP[10] and ground type "C" according to the EC-8[12]. The Vs profile was developed (fig. 4) for the Amaravati region for the least value of average Vs (up to 30 meters depth) among all, because the entire site class is showing one particular classification (i.e. class D). The response analysis is performed for the same soil profile of minimum V_s^{30} using representative input motions. Unfortunately, the records of strong motion are not available for the south India region.

Therefore, the recorded ground motions were obtained from the data source center of COSMOS. The response analysis was carried out using four different earthquake acceleration time histories of 2001 Bhuj, 1995 Chamba, 1994 Northridge and 1991 Uttarkashi. The surface PGA is determined for all selected input motions and it is observed from the results the minimum value of PGA is 0.27 g and the maximum PGA is 0.29 g. The predominant zone of the frequency concerning maximum amplitudes has been summarized for input motion types and the frequency is varying from 0.2 Hz to 6.58 Hz. The response spectrum between the outcrop of the bedrock to the free field is also compared in this study. Finally, the normalized response spectra for all input motion are drawn for the spectral periods of BIS code for medium soil[19].

References

1. Abrahamson N., Atkinson G., Boore D., Bozorgnia Y., Campbell K., Chiou B., Idriss I.M., Silva W. and Youngs R., Comparisons of the NGA ground-motion relations, *Earthquake Spectra*, **24(1)**, 45-66 **(2008)**

2. American Society of Civil Engineers (ASCE), Minimum design loads for buildings and other structures, Reston, VA, ASCE Standard, 650 **(2010)**

3. Anbazhagan P. and Sitharam T.G., Seismic microzonation of Bangalore, India, *Journal of Earth System Science*, **117(2)**, 833-852 **(2008)**

4. Anbazhagan P., Kumar A. and Sitharam T.G., Seismic site classification and correlation between standard penetration test N value and shear wave velocity for Lucknow City in Indo-Gangetic Basin, *Pure and Applied Geophysics*, **170(3)**, 299-318 **(2013)**

5. Anbazhagan P., Sheikh M.N. and Parihar A., Influence of rock depth on seismic site classification for shallow bedrock regions, *Natural Hazards Review*, **14(2)**, 108-121 **(2013)**

6. Bajaj K. and Anbazhagan P., Site Amplification Factors and Acceleration Response Spectra for Shallow Bedrock Sites–Application to Southern India, *Journal of Earthquake Engineering*, **24(1)**, 1-21 **(2020)**

7. Bergamo P., Comina C., Foti S. and Maraschini M., Seismic characterization of shallow bedrock sites with multimodal Monte Carlo inversion of surface wave data, *Soil Dynamics and Earthquake Engineering*, **31(3)**, 530-534 **(2011)**

8. Boore D.M., Estimating V s (30) (or NEHRP site classes) from shallow velocity models (depths< 30 m), *Bulletin of the Seismological Society of America*, **94(2)**, 591-597 **(2004)**

9. Boore D.M., Thompson E.M. and Cadet H., Regional correlations of VS 30 and velocities averaged over depths less than and greater than 30 meters, *Bulletin of the Seismological Society of America*, **101(6)**, 3046-3059 **(2011)**

10. Building Seismic Safety Council (BSSC), NEHRP recommended provisions for seismic regulations for new buildings and other structures, 2000 Ed., Part 1, Provisions, Rep. No. FEMA 368, FEMA, Washington, DC **(2001)**

11. Dikmen Ü., Statistical correlations of shear wave velocity and penetration resistance for soils, *Journal of Geophysics and Engineering*, **6(1)**, 61-72 **(2009)**

12. Eurocode 8, Design of structures for earthquake resistance, part 1, General rules, seismic actions and rules for buildings, EN 1998-1, European Committee for Standardization (CEN), http://www.cen.eu/cenorm/homepage, (last accessed September 2020) **(2004)**

13. Hadley D.M., Helmberger D.V. and Orcutt J.A., Peak acceleration scaling studies, *Bulletin of the Seismological Society of America*, **72(3)**, 959-979 **(1982)**

14. Hanumantha Rao C. and Ramana G.V., Site specific ground response analyses at Delhi, India, EJGE, 14(D) **(2009)**

15. Hanumantharao C. and Ramana G.V., Dynamic soil properties for microzonation of Delhi, India, *Journal of Earth System Science*, **117(2)**, 719-730 **(2008)**

16. Hashash Y.M.A., Musgrove M.I., Harmon J.A., Ilhan O., Xing G., Groholski D.R., Phillips C.A. and Park D., DEEPSOIL 7.0, User Manual, Urbana, IL, Board of Trustees of University of Illinois at Urbana-Champaign **(2020)**

17. Imai T. and Yoshimura Y., The relation of mechanical properties of soils to P and S-wave velocities for ground in Japan, Technical note OYO Corporation **(1975)**

18. Indian Standard, IS 1498:1970, Classification and Identification of Soils for general Engineering purposes, First revision, Bureau of Indian Standard, New Delhi **(2000)**

19. Indian Standard, IS 1893 (Part I), Criteria for earthquake resistance design of structures, Part-I, Bureau of Indian Standard, New Delhi **(2016)**

20. IS 2131: 1981 Indian Standard Method for Standard Penetration Test for soils, Bureau of Indian Standards, New Delhi **(1982)**

21. Kirar B., Maheshwari B.K. and Muley P., Correlation between shear wave velocity (Vs) and SPT resistance (N) for Roorkee region, *International Journal of Geosynthetics and Ground Engineering*, **2(1)**, 1-11 **(2016)**

22. Kramer S.L., Geotechnical earthquake engineering, In Prentice Hall international series in civil engineering and engineering mechanic **(2005)**

23. Kumar A., Anbazhagan P. and Sitharam T.G., Site specific ground response study of deep Indo-Gangetic Basin using representative regional ground motions. In Geo Congress 2012: State of the art and practice in geotechnical engineering, 1888-1897 **(2012)**

24. Kuo C.H., Wen K.L., Hsieh H.H., Lin C.M., Chang T.M. and Kuo K.W., Site classification and Vs30 estimation of free-field TSMIP stations using the logging data of EGDT, *Engineering Geology*, **129(130)**, 68-75 **(2012)**

25. Maheswari R.U., Boominathan A. and Dodagoudar G.R., Use of surface waves in statistical correlations of shear wave velocity and penetration resistance of Chennai soils, *Geotechnical and Geological Engineering*, **28(2)**, 119-137 **(2010)**

26. Naik S.P., Patra N.R. and Malik J.N., Spatial distribution of shear wave velocity for late quaternary alluvial soil of Kanpur city, Northern India, *Geotechnical and Geological Engineering*, **32(1)**, 131-149 **(2014)**

27. National Research Council Canada (NRCC), National Building Code of Canada (NBCC), NRCC-47666, Ottawa, Canada **(2005)**

28. NDMA, Development of probabilistic seismic hazard map of India, Technical report by National Disaster Management Authority, Govt. of India **(2010)**

29. Ohsaki Y. and Iwasaki R., On dynamic shear moduli and Poisson's ratios of soil deposits, *Soils and Foundations*, **13(4)**, 61-73 **(1973)**

30. Panjamani A., Kumar Katukuri A., Gr R., Moustafa S.S. and Al-Arifi N.S., Seismic site classification and amplification of shallow bedrock sites, *Plos One*, **13(12)**, 1-22 **(2018)**

31. Phanikanth V.S., Choudhury D. and Reddy G.R., Equivalent-linear seismic ground response analysis of some typical sites in Mumbai, *Geotechnical and Geological Engineering*, **29(6)**, 1109-1126 **(2011)**

32. Puri N., Jain A., Mohanty P. and Bhattacharya S., Earthquake response analysis of sites in state of Haryana using DEEPSOIL software, *Procedia Computer Science*, **125(1)**, 357-366 **(2018)**

33. Putti S.P., Devarakonda N.S. and Towhata I., Estimation of ground response and local site effects for Vishakhapatnam, India, *Natural Hazards*, **97(2)**, 555-578 **(2019)**

34. Rahman M.Z., Kamal A.M. and Siddiqua S., Near-surface shear wave velocity estimation and V s 30 mapping for Dhaka City, Bangladesh, *Natural Hazards*, **92(3)**, 1687-1715 **(2018)**

35. Reddy M., Konda R.R., Kumar G.K. and Asadi S.S., Site Characterization and Evaluation of Seismic Sources for Amaravati Region, *International Journal of Geotechnical Earthquake Engineering*, **11(1)**, 71-86 **(2020)**

36. Satyam N.D. and Towhata I., Site-specific ground response analysis and liquefaction assessment of Vijayawada city (India), *Natural Hazards*, **81(2)**, 705-724 **(2016)**

37. Seed H.B., Wong R.T., Idriss I.M. and Tokimatsu K., Moduli and damping factors for dynamic analyses of cohesionless soils, *Journal of Geotechnical Engineering*, **112(11)**, 1016-1032 **(1986)**

38. Shukla J. and Choudhury D., Seismic hazard and site-specific ground motion for typical ports of Gujarat, *Natural Hazards*, **60(2)**, 541-565 **(2012)**

39. Vucetic M. and Dobry R., Effect of soil plasticity on cyclic response, *J. Geotech. Eng.-ASCE*, **117(1)**, 89–107 **(1991)**

40. Wang H.Y. and Wang S.Y., A new method for estimating VS (30) from a shallow shear-wave velocity profile (depth< 30 m), *Bulletin of the Seismological Society of America*, **105(3)**,1359-1370 **(2015)**.

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