17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

SITE CHARACTERIZATION AND SOIL STRUCTURE INTERACTION WITH DEEP BEDROCK DEPTH IN INDO- GANGETIC PLAINS

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Abstract

Local site effects are highly responsible in causing damage to structures during earthquakes. Thus, one of the aim of seismologists and geotechnical engineers is to characterize the soil for the region prior for seismic hazard assessment. In the present work, an endeavor is made to study the depth of bedrock in Indo-Gangetic Plains from Seismotectonic Atlas of India [1]. A huge variation of bedrock depth ranging from 0-4000m indicates the presence of thick soil cover in the study region. Roorkee city, situated in the foothills of Himalayas has a bedrock depth of around 3000m and due to presence of this huge soil cover, the occurrence of any great seismic event will pose a threat to both life and property as properties of propagating waves change as they travel towards the surface. The site characterization is carried out by MASW and Microtremor methods and shear wave velocity profiles are estimated with thickness of soil. The region falls in Site Class D. Ground response analysis is carried out for a scenario earthquake MW=8.0 taking Himalayan Frontal Thrust (HFT) as the source using STRATA [2]. Moreover, analysis of resonance is done for low to high rise buildings having 13-150 m height. Moderate rise buildings (40-110m) are affected by resonance and other buildings are unaffected. This kind of study will be very helpful for future planning in more accurate seismic-hazard assessment and disaster mitigation planning for this region.

Keywords: Site Characterization; MASW; Microtremor; Shear Wave Velocity; Resonance

1. Introduction

About 59% of India's land mass is at a risk of moderate to rigorous seismic hazard covering many important cities, as given in seismic zoning of the country. The surface ground motion in comparison to bedrock motion is highly influenced by the local site conditions. The presence of loose material on the bedrock amplifies the incoming waves as they travel towards the surface causing damage to both life and property. The recently experienced large earthquakes caused heavy damage at epicentral distances ranging from 250-500 km or so due to local site conditions. For example, in 1985 Michoacan earthquake, major damage was observed at 200 miles away from the epicenter in Mexico City. Similarly, in Bhuj earthquake, 2001, heavy damage was seen in multistory building at an epicentral distance of 350 km in Ahmedabad City.

Himalayan region is the most seismically active regions due to the accumulation of heavy strains. Many researchers [3, 4] have predicted the presence of a seismic gap in this region. Moreover, the probability of occurrence of a great seismic event is 0.59 in the next 100 years [5]. The Indo-Gangetic Basin (IGB) lies parallel to the Himalayas and is highly populated. The basin is formed by the loose soil deposits and any future earthquake in the Himalayas will lead to massive destruction and will pose a threat to both life and property. Many studies in India to estimate the effect of local site conditions have been done by many authors [6, 7]. [8] studied the effect of soil cover and the influence of soil type on deep soil response. The site response study for Delhi region was done by [9]. [10] developed a correlation between VS and N for all types of soils, clay soils and sandy soil for Roorkee region. The insitu tests and laboratory tests were used to obtain the dynamic properties of soil in Italy by [11]. [12] used the GR relationship and the Gumbel's annual extreme value method to see the effect on b-value of Sylhet region. [13] reported the anomalous behavior of Radon isotope pairs at Mat fault, Mizoram (India) in different depths of soil. Hence, it becomes necessary to consider these local site conditions in order to predict the seismic hazard before the occurrence of an earthquake and proper mitigations measures can be taken for the infrastructures.

In the present paper, firstly, the variation of bedrock depth in the Indo-Gangetic Plains is studied using GSI (2000). Secondly, shear wave velocity is estimated up to depth 500 m using the joint fit inversion technique from dispersion curves obtained from multichannel analysis of surface wave (MASW) and horizontal to vertical spectral ratio curves from microtremor measurements using Nakamura's method [14] for Roorkee city having deep bedrock depth of around 3000m. The city falls in Site Class D as per NEHRP Site Classification based on the shear wave velocity at a 30m depth of soil. Thirdly, site response analysis is carried out using STRATA for a future scenario earthquake (Mw= 8.0) occurring in the proximity of Himalayan Frontal Fault to study the amplification in the region due to local site effects. Moreover, soil structure resonance analysis is carried out by considering the dominant periods of buildings having three to thirty-six floors and the dominant period of soil.

2. Indo-Gangetic Plains

The Indo-Gangetic Plains (approximately between longitude 77^0E -88^0E and latitude 24^0N-30^0N) lies in between the Himalayas and the Indian Shield and covers an area of about 250,000 km^2. Ganga plain have a great variation in width lying between 200-450 km and the length is about 1000 km. Fig. 1 describes the study area in which densely populated cities like Lucknow, Delhi, Kanpur, Agra, Meerut and Allahabad are shown. Moreover, it can also be observed from the Fig. 1 that there exists an asymmetry in the sediment thickness of the basin. The sedimentary thickness of 3-4 km is seen in the north of Indo-Gangetic Basin (IGB), while, in south of IGB, thickness is about 0.5 to 1 km. Also, in the eastern part of IGB, thickness varies to about 2-2.5 km. The Indo-Gangetic Basin is under a risk of seismic hazard as it lies very close to Himalayan belt.

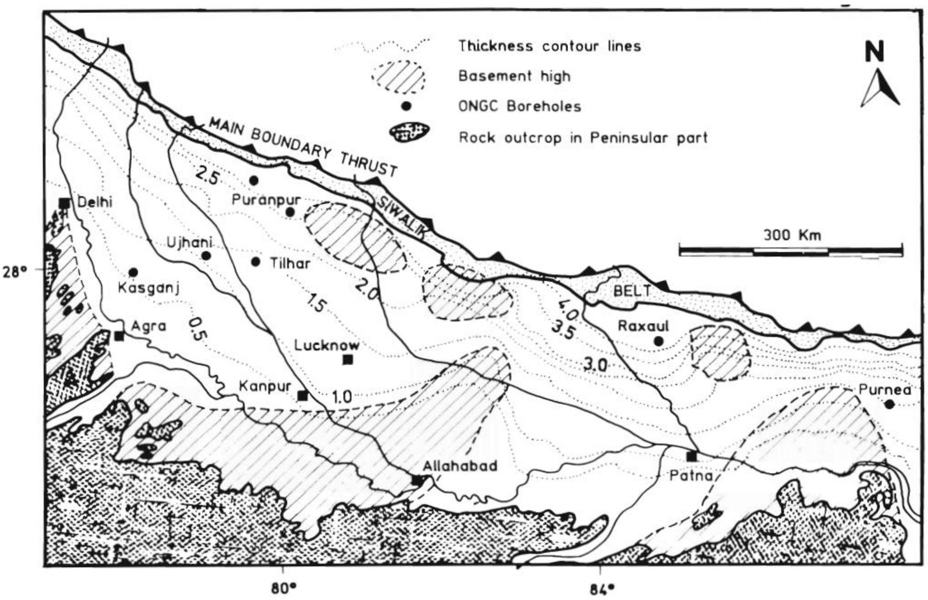

Fig. 1 Contours of sediment thickness of the IGB (Singh, 1996)

The Himalayan arc consists of Higher Himalayas, Lesser Himalayas and Outer Himalayas longitudinal zones running from north to south over a 2900 km distance. Higher Himalayas consists of crystalline and metamorphic rocks, while, Lesser Himalayas consists of Precambrian sequences and Outer Himalayas consists of fluvial sediments. In the southern sides, all these longitudinal zones are bounded by Main Boundary Thrust (MBT), Main Central Thrust (MCT) and Himalayan Frontal Thrust (HFT) respectively. Additionally, all of the three thrusts have developed from north to south. Many moderate to great earthquakes have occurred in the proximity of the Indo-Gangetic Plain, namely, Garhwal earthquake of Mw 8.0 (1803), Dhubri earthquake of Mw 7.1 (1930), Bihar-Nepal earthquake of Mw 8.1 (1934), Bihar-Nepal earthquake of Mw 6.8 (1988).

3. Site Characterization

One of the important parameter in understanding the dynamic behavior of soil is shear wave velocity(Vs). Moreover, it can be used for the determination of shear modulus (G) of soil as well as for the site characterization applications of geotechnical earthquake engineering. The depth of bedrock is estimated from Seismotectonic Atlas of India [1] in which contours represents the bedrock depth of a place. A wide variation in depth of bedrock is observed ranging from 0m to 3000m near Roorkee city. Hence, 15 sites of this city, are explored using geophysical methods. These sites are located at a distance of about 2-3 km from each other. Fig. 2 shows the sites considered in Roorkee city for characterization. In Roorkee East, six sites are taken (Sites 1-6), in Solani River, three sites are selected (Sites 7-9) and in Roorkee West, six sites are chosen (Sites 10-15). In the field set up, two tests were performed. Firstly, active MASW consisting of Soil Spy Rosina as a data acquisition system. Secondly, HVSR of Microtremor was performed in which Tromino was used as a data acquisition system.

The set up used for investigating the subsurface materials for upper layers consisted of nine sensors with 2m inter geophone spacing. For setting out a trigger, first geophone from the source was used. In order to characterize to deeper soil, the use of microtremor with passive source was explored. For HVSR analysis, this instrument has been used to record ambient vibrations for 20 minutes at each location. Grilla [15] software is used for the analysis of the data recorded in the field using Soil Spy Rosina and Tromino. After obtaining both the curves, i.e., dispersion curves and HVSR curves, Join Fit module in the Grilla software is utilized where both the curves are placed together simultaneously for the estimation of shear wave velocity profile of deeper layers of soil.

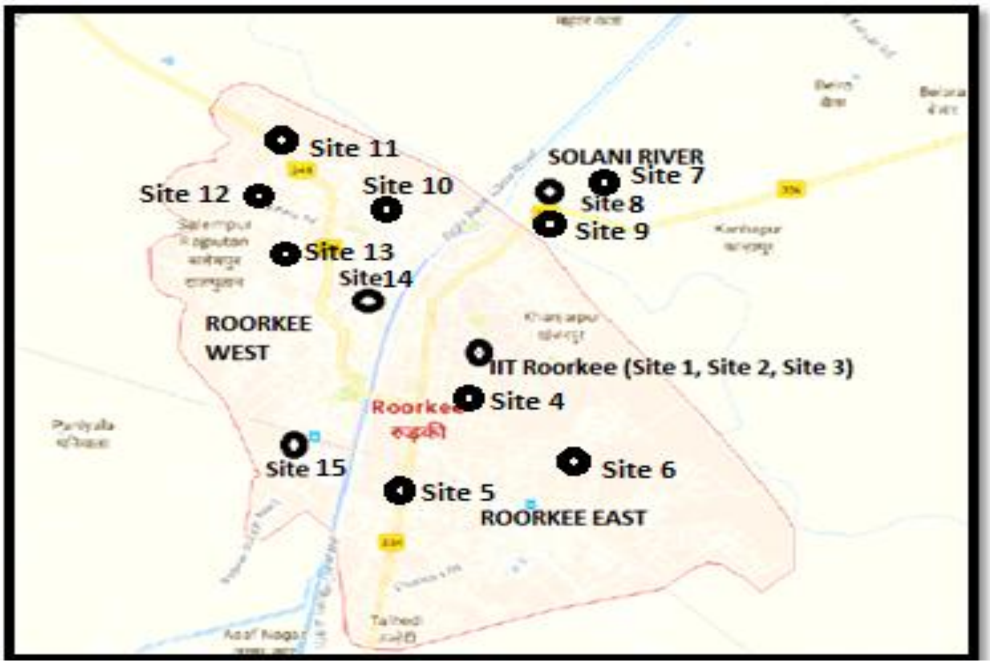

Fig. 2 Sites considered for characterization in Roorkee

For seismic site classification, time averaged shear wave velocity in the upper 30 m (V_{S30}) is used as proposed by [16]. The V_{S30} is estimated as follows:

$$V_{S30} = \frac{30}{\sum_{i=1}^{m} \frac{H_i}{V_{Si}}} \tag{1}$$

where, H_i shows the thickness of layer i, m is the number of layers in upper 30 m of soil and V_{Si} is the shear wave velocity of layer i. The classification of sites is based as per National Hazard Reduction Program (NEHRP). For site class A ($V_{S30} > 1500$ m/s), Site class B ($760 < V_{S30} < 1500$ m/s), Site class C ($360 < V_{S30} < 760$ m/s) and for Site class D ($180 < V_{S30} > 360$ m/s). The shear wave velocity at 15 sites lies between 260-300 m/s and the city falls in Site class D.

Fig. 3 (a, b and c) shows the graphical representation of shear wave velocity profile of all the sites where vertical axis represents the estimated depth (m) and the horizontal axis represents the shear wave velocity V_S (m/s). Fig. 3(a) shows the estimated shear wave velocity profiles for Roorkee East. As expected and seen from the Figure, the shear wave velocity increases as depth increases. The shear wave velocity (V_{s30}) of all the sites in this region is about 250-300 m/s Fig. 3(b) shows the estimated shear wave velocity profiles for sites near Solani River. The shear wave velocity (V_{s30}) of all the sites in this region is about 200-250 m/s. Fig. 3(c) shows the estimated shear wave velocity profiles for Roorkee West. The shear wave velocity (V_{s30}) of all the sites in this region is about 240-300 m/s.

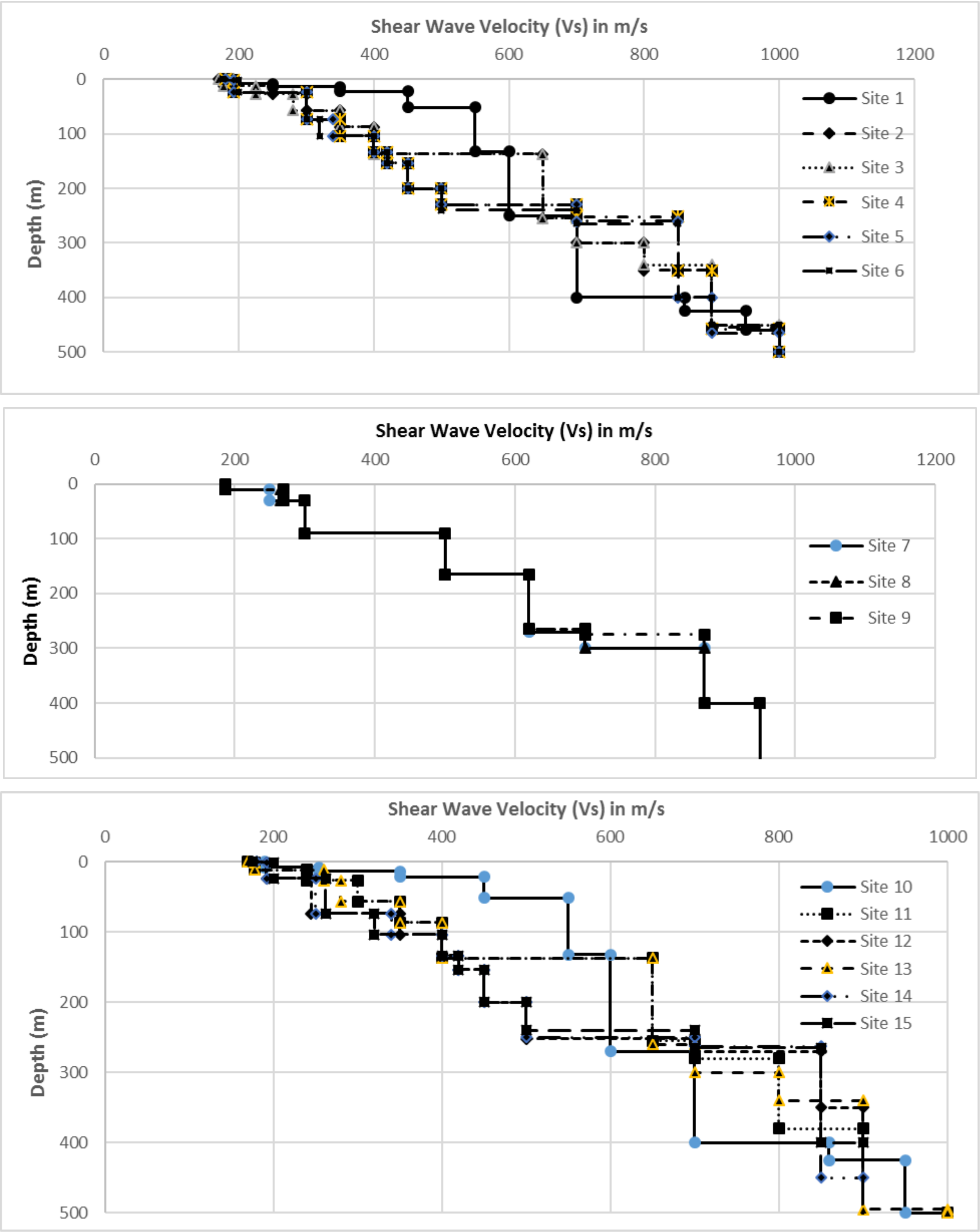

Fig. 3 (a) Shear wave velocity profiles for Roorkee East (b) Solani River and (c) Roorkee West.

4. Site Response Analysis

Site response analysis helps in the study of the response of surface ground motion characteristics of the given soil column to the input ground motion. Many site response software's, namely, SHAKE, EERA, STRATA and DEEPSOIL etc. are available requiring the modeling of the soil column and solving the one-dimensional wave propagation equation. The computer program STRATA is used for the ground response analysis in this study. It uses the time domain input motions for equivalent linear site response analysis and properties of soil can also be randomized. The input parameters are the thickness of the layer, unit weight, shear wave velocity of the layer and the bedrock depth. The shear modulus reduction curves and the damping curves given by [17] for different soil types is used site response study. A scenario earthquake of M_w=8 with reverse slip mechanism and dip (45^0) having Himalayan Frontal Thrust (HFT) as source is used to study the response of the all site class A, B, C and D at rupture distance ranging from 1- 100 km. The bedrock level ground motions are determined using the attenuation equation given by [18] in NGA WEST 2 project. For active crustal regions, the NGA-West2 project is a multidisciplinary research program that addresses several issues in estimation of ground-motion hazard. Fig. 4 shows the variation of PGA with the rupture distance for all the site classes. Roorkee is situated at a distance of about 25km from Himalayan Frontal Thrust (HFT) and the PGA is 0.4g. The synthetic acceleration time series is used as input ground motions at the bedrock.

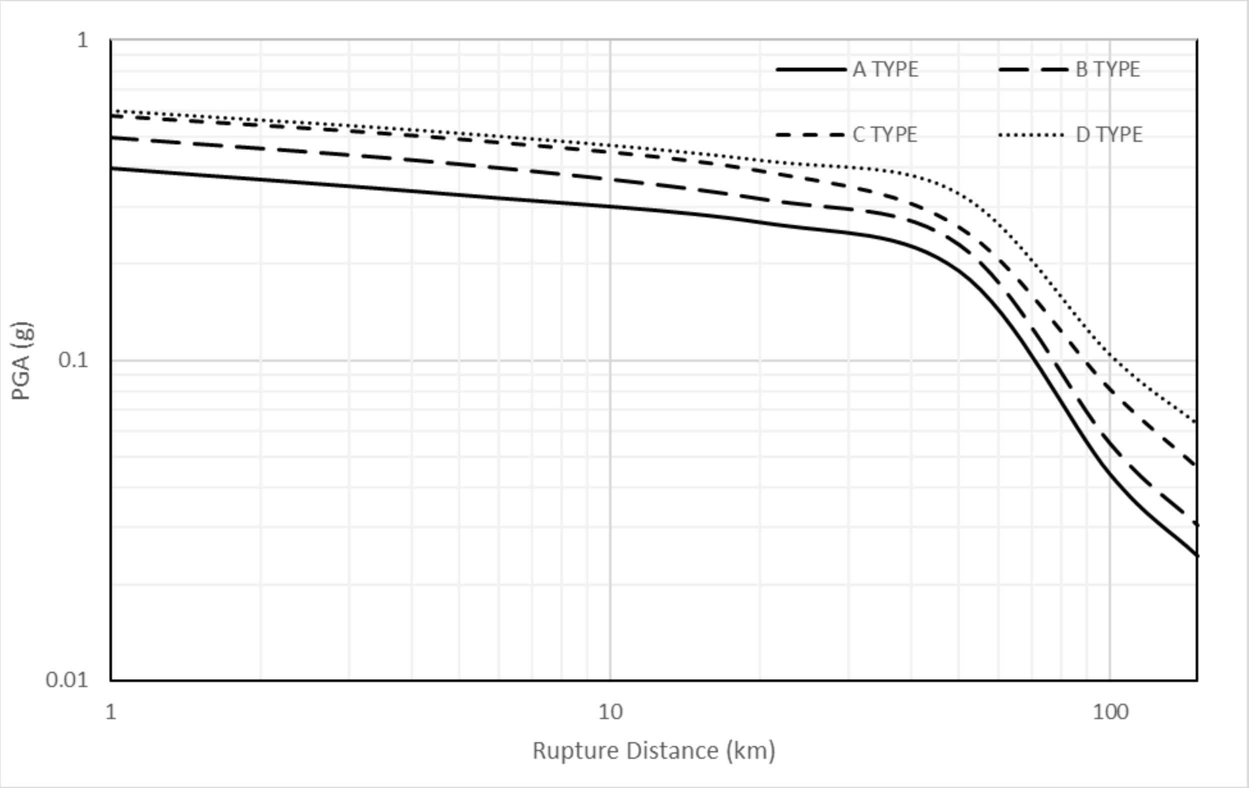

Fig. 4 Variation of PGA with rupture distance for all site A, B, C and D type sites

The fundamental period of the soil column was estimated by using the equation proposed by [19] with the help of shear wave velocity and thickness of each layer. The dominant period of soil is from 0.9s to 1.25 s and the natural frequency of the soil is low which lies between 0.8 -1.3 Hz. Fig. 5 shows the plot of amplification ratio with the natural frequency at the surface of soil. It can be seen that in the dominant frequency of soil, amplification factor is maximum i.e. around 5 and as the frequency increases amplification factor reduces to about 3. Fig. 6 shows the amplification of different layers of soil at depths of 10m, 20m, 30m and 50 m from the surface. As expected and seen from the Fig., seismic waves get amplified as they reach the surface. Moreover, maximum amplification of all the layers is in low frequency range due to resonance phenomenon. At a depth of 50m, the amplification factor is about 1.2 and at 30m, it increases to 2.3 and at 20m it is maximum and reaches 3.2, however, at a depth of 10m, amplification factor is about 2.8. In frequency range from 5-8 Hz, amplification factor reduces for all the layers and maximum value is 1.6. Further, increase in natural frequency of more than 10 Hz, deamplification of all motions occurs as soil column is unable to transmit the high inertial forces in this frequency range.

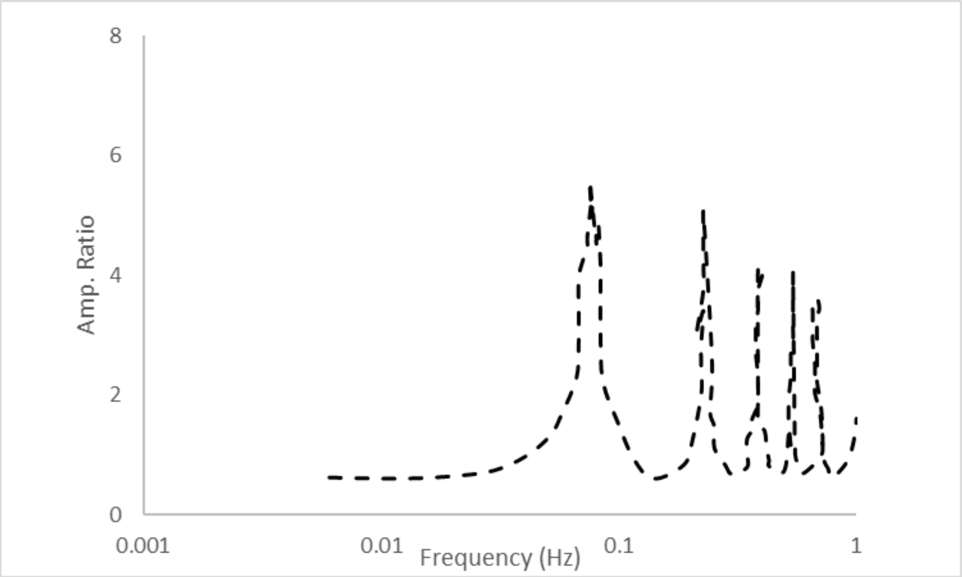

Fig. 5 Amplification on surface of soil due to input motion

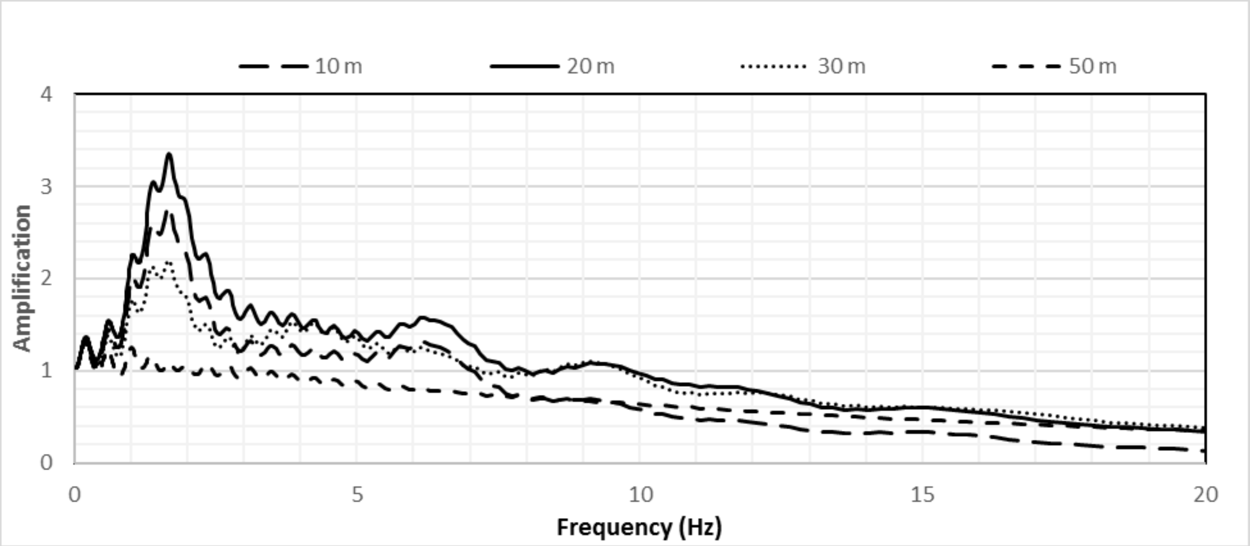

Fig. 8 Amplification of different layers of soil in different frequency range

5. Resonance of Structures

The empirical relationships between the fundamental period of buildings and number of floors or with the height of buildings helps the seismologists to study the response of buildings in any future occurring seismic event at a site due to resonance. Twelve low to high rise buildings are considered in the study region with varying heights from 13 m to 150 m having 3 to 36 floors respectively. The shortest building (N1) is of height 13 m and the tallest building (N12) is of height 150 m. Table 1 shows the description about the building along with the dominant period of building by using the empirical equation [20] as follows:

$$T= 0.016H \qquad (2)$$

where T is the dominant period of the building and H is the height of the building. The matching of the dominant period of soil and the building will cause soil- structure resonance. The dominant period of soil obtained lies between 0.9s to 1.25s. It can be observed from the Table 1, N3 to N9 buildings are affected by soil structure resonance while in other buildings, no resonance is observed as time period of buildings are less in N1 and N2 buildings and time periods of N10 to N12 buildings are more than the dominant period of soil.

Table 1- Description of Buildings with time periods of soil and buildings

Building	Height (m)	No. of Floors	Time Period of Building (s)	Dominant Period of Soil (s)
N1	13	3	0.208	1.11
N2	25	6	0.4	1.01
N3	40	9	0.64	0.9
N4	52	12	0.832	1.12
N5	62	15	0.992	1.05
N6	75	18	1.2	1.07
N7	84	21	1.344	1.13
N8	100	24	1.6	1.12
N9	110	27	1.76	1.25
N10	123	30	1.968	1.11
N11	135	33	2.16	1.03
N12	150	36	2.4	1.11

6. Conclusions

In this study, the bedrock depth in Indo-Gangetic Plains is determined from GSI (2000) and a wide variation in depth of bedrock is observed from 0m to 4000m.The shear wave velocity profiles are determined for the study region from MASW and Microtremor measurements. The region has lower values of shear wave velocity ranging from 260- 300 m/s and falls in Site Class D according to NEHRP. The dominant period in the region is more than 1 s indicating the presence of thick soil cover. Ground response analysis is carried out using STRATA and amplification factor is maximum i.e. around 5 at the surface of soil, but, is in the range of 3.3 to 1.4 for different layers of soil at different depths. The study of the resonance phenomenon for analysis of soil structure interaction is carried out for twelve buildings (N1-N12) ranging from 13-150m in height. It was observed that N3 to N9 buildings are affected by soil structure resonance while in other buildings, no resonance is observed as time period of buildings are less in N1 and N2 and more in N10 to N12 in comparison to the dominant period of soil. Hence, high rise buildings having nine to twenty-seven floors are under a risk of resonance in this region. However, important structures i.e. educational institutions, offices, hospitals usually have less than ten floors and possess lower risk of resonance. Thus, effect of resonance must be considered in designing of new buildings.

6. References

[1] GSI (2000): Seismotectonic Atlas of India and Its Environs, *Geological Survey of India*, Bangalore.

[2] Kottke AR, Wang X, Rathje EM (2013): Technical Manual of STRATA, *Geotechnical Engineering Center, Department of Civil, Architectural and Environmental Engineering,* University of Texas.

[3] Gahalaut VK, Chander R (1997): On Interseismic elevation changes and strain accumulation for great thrust earthquakes in Nepal Himalaya, *Geophys. Res. Lett.*, 24, 1011-1014.

[4] Bilham R, Blume F, Bendick R, Gaur VK (1998): Geodetic constraints on the Translation and Deformation of India: implications for future great Himalayan earthquakes, *Current Science*, 74(3), 213–229.

[5] Khattri KN (1999): An Evaluation of earthquakes hazard and risk in northern India, *Himalayan Geology*, 20, 1-46.

[6] Anbazhagan P, Sitharam TG (2008): Spatial variability of the weathered and engineering bedrock using multichannel analysis of surface wave survey, *Pure Appl. Geophys*., 166(3), 409–428.

[7] Desai SS and Choudhury D (2015:) Site-specific seismic ground response study for Nuclear power plants and ports in Mumbai, *Nat Hazards Rev*, doi: 10.1061/ (ASCE) NH.15276996.0000177.

[8] Jakka RS., Hussain M, Sharma, ML (2015): Effects on amplification of strong ground motion due to deep soils, *Geomechanics and Engineering*, 8(5), 663-674.

[9] Kumar A, Bora O, Harinarayan NH (2016): Obtaining the surface PGA from site response based on globally recorded ground motions and matching with the codal values, *Nat Hazards*, 81, 543-572.

[10] Kirar B, Maheshwari BK, Muley P (2016): Correlation between shear wave velocity (Vs) and SPT resistance (N) for Roorkee region, *International Journal of Geosynthetics and Ground Engineering*, 2(1), 9.

[11] Cavallaro A, Castelli F, Ferraro A, Grasso S, Lentini V (2017): Site response analysis for the seismic improvement of an historical and monumental building: the case study of Augusta Hangar, *Bulletin of Engineering Geology and the Environment*, 1–32.

[12] Ray S, Alam MJ, Haque M, Das SK, Tanmoy BB, Hasan MN (2019): A study on b-value and investigation of seismic hazard in Sylhet seismic region, Bangladesh using Gumbel’s extreme value distribution method, *SN Applied Sciences*, 1(5), 435.

[13] Thuamthansanga T, Sahoo BK, Tiwari RC, Sapra BK (2019): A study on the anomalous behaviour of Radon in different depths of soil at a tectonic fault and its comparison with time-series data at a distant continuous monitoring station, *SN Applied Sciences*, 1(7), 683.

[14] Nakamura Y (1989): A method for dynamic characteristics estimation of sub-surface using microtremor on the ground surface, *Quarterly Report of Railway Technical Research Institute*, 30, 25–33.

[15] Micromed S. p. A. (2008): Soil Spy Rosina User’s Manual, Ver. 2.0, Treviso, Italy.

[16] Dobry R, Borcherdt R D, Crouse C B, Idriss I M, Joyner W B, Martin G R, Power M S, Rinne E E and Seed R B (2000): New site coefficients and site classification system used in recent building seismic code provisions, *Earthquake Spectra*, 16, 41–67.

[17] Seed HB, Idriss IM (1970): Analyses of ground motions at Union Bay, Seattle during earthquakes and distant nuclear blasts, *Bulletin of the Seismological Society of America*, 60(1),125-36.

[18] Boore, DM, Stewart JP, Seyhan E and Atkinson GM (2014): NGA-West2 equations for predicting PGA, PGV, and 5% damped PSA for shallow crustal earthquakes, *Earthquake Spectra*, 30, 1057–1085.

[19] Kanai K (1951): Relation between the nature of the surface layer and the amplitude of earthquake motions, *Bulletin of the Tokyo Earthquake Res. Institute*, 51-03.

[20] Gallipoli MR, Mucciarelli M, Šket-Motnikar B, Zupanćić P, Gosar A, Prevolnik S, Herak M, Stipčević J, Herak D, Milutinović Z, Olumćeva T (2010): Empirical estimates of dynamic parameters on a large set of European buildings, *Bulletin of earthquake engineering*,8(3), 593-607.