SITE RESPONSE STUDY OF A DEEP BASIN CONTAGIOUS TO ACTIVE REGION- UTTAR PRADESH REGION, INDIA

Ketan BAJAJ1, P. ANBAZHAGAN2

ABSTRACT

Uttar Pradesh region (UPR) of India had experienced catastrophic earthquake damages due to the presence of thick soil depth of 0.05 km to about 4 km. However, very few studies have been carried out to characterize the UPR soil up to the shallow depth and very limited attempts have been made to measure the dynamic properties for deeper depths. Hence, in this study, firstly, the shear velocity profile up to 300 m depth is measured using combined active and passive multichannel analysis of surface wave (MASW) survey in 75 selected locations in UPR. Further, these sites are classified and characterized based on time-averaged in the upper 30 m depth as per NEHRP seismic site classification. The measured $V_s$ profiles are used to estimate the site-specific response parameters at different locations by carrying out non-linear site response analysis. Input ground motions are selected from the worldwide-recorded database based on the seismicity of the region. Shear modulus and damping curve are selected based on the stratigraphical variation of the soil column in UPR. Based on the analysis, it has determined that for the amplification range of site class E, D, C and B is 2.35 to 7.58, 1.82 to 5.58, 1.5 to 4.92 and 1.23 to 3.25 respectively. The first time, representative site response for deep soil column and amplification factors for the different periods for different seismic site class are estimated for UPR region which would be further useful in developing a design response spectrum for deep deposits in India.

Keywords: Deep basin, response spectra, site response, Uttar Pradesh

1. INTRODUCTION

Local site conditions have great influence on ground surface motion and structural damage caused by any earthquake event. Two classic examples that exemplify the influence of site amplification due to local site effect are 1985 Mexico earthquake and the 1989 Loma Prieta earthquake. Similarly, many earthquakes in India (1934 Bihar-Nepal; 2001, Bhuj; 2015 Nepal earthquake) have also highlight the local site effect.

The Indian subcontinent is one of the most seismically active regions in the world. The ongoing collision between the Indian and Eurasian Plate is building the strain along and within the plate boundary. Moreover, crustal shortening along its northern edge increases the earthquake hazard, particularly in the Northern part Indian Subcontinent. Various authors (Bilham, 2005; 2001) have studied the seismotectonic of the Himalayan region and predicted the high seismicity along the entire stretch of the Main Boundary thrust (MBT), the Main Central thrust (MCT) and Indus-Tsangpo Suture (ITS). In the last two centuries, the Himalayan region has experienced many events of magnitude more than 8. The highly fertile and deep basin of Uttar Pradesh Region (UPR), bound on the north side of the Himalayas, is one of the most populous areas. It is about 500 km long to the south is filled-up in

1PhD Student, Bangalore, India, ketanbajaj@iisc.ac.in
2Associate Professor, Department of Civil Engineering, IISc, Bangalore, India, anbazhagan@iisc.ac.in
the form of loose soil deposits. Additionally, surrounded by high seismic region make the scenario more destructive and may result in causalities to human life or infrastructure from any large earthquake in the future. Hence, there is a need to study the local site effect due to deep deposits in UPR contagious with high seismic region. The poor characterization of deep soil deposits in UPR also set the priority for determination of its seismic site classification and amplification factor for different periods due to local site effect.

Various authors (Boominathan et al., 2008; Anbazhagan and Sitharam, 2008; Anbazhagan et al., 2010; Kumar et al., 2012; Desai and Choudhury, 2014, 2015; Kumar et al., 2016) in India have attempted to estimate the local site effect. However, most of these earlier works either provided guidelines or preliminary study for performing site response studies. Moreover, very few studies estimated the local site effects for IGB. Anbazhagan et al. (2011) performed the site response analysis for limited sites at Dehradun, Lalu and Najibabad based on the collected borehole data and using synthetic ground motion for 1999 Chamoli EQ. Kumar et al. (2012) performed the site response analysis for typical sites at Lucknow using synthetic and recorded ground motions. Kumar et al. (2016) performed the site response study for Delhi region using the equivalent linear model. Most of the previous studies are limited to soil column of 30 m depth, additionally, in many of the studies, measured SPT-N values were converted to $V_s$ profiles and used for site response studies. Moreover, in the previous site response studies, the input ground motions were either selected randomly from global database or simulated based on the occurred earthquake scenario. Till today there are no studies available for determining the local site effect for the deep deposits of UPR from the measured $V_s$ profiles more than 100 m.

The first aim of the study is to develop the shear velocity ($V_s$) profile up to 200 m depth using combined active and passive multichannel analysis of surface wave (MASW) survey for deep deposits in Uttar Pradesh Region, India. Geophone of 2 Hz frequency has been used for performing the MASW survey in the entire stretch of UHR. Ambient noise has been used as a source for passive MASW survey. Recordings have been done at different sampling interval and record lengths. The sites are further classified and characterized based on time-averaged $V_s$ in the upper 30 m depth as per NEHRP (BSSC, 2003) seismic site classification. Secondly, non-linear site response analysis has been carried out. Site response study focuses on estimation of the site amplification for deep deposits and development of a model for nonlinear soil response for possible use of ground motion developers. The input ground motions are selected based on seismicity of the region by considering global and locally available recorded ground motions. Finally, the site amplification factor has been given for different seismic site class, which would be further useful in developing new ground motion considering site amplification model and design response spectra for deep deposits in India.

2. STUDY AREA

The Uttar Pradesh Plain is well known as the Himalayan fore-deep lies in between the Indian Shield and the Himalayas in Indo-Gangetic Basin. The Ganga Plain extends from Aravalli-Delhi Ridge in the west to the Rajmahal hills in the east; Himalayan foothills in the north to the Bundelkhand-Vindhyan Plateau in the south, occupying an area around 250,000 km$^2$, roughly between longitude 77°E, and 84°E and latitude 24°N and 30°N. The length of the Ganga plain in UPR is about 800 km; the width is variable, ranging from 200 to 450 km, being wider in the western part and narrower in the eastern part. Figure 1 shows the boundary of the study area considered in our study. The region has an average population > 600 million (as per 2011 census) and encompasses densely populated cities like Lucknow, Kanpur, Meerut, Agra, Allahabad, and Varanasi. A strong asymmetry can be seen in thickness of the foreland basin of UPR. Northwards the thickness of sediments is around 3-4 km near the Siwalik Hills. The maximum estimated thickness of sediment in the Siwalik belt is about 6-8 km. Thickness of sediments varies from 0.5 to 1.0 km Southwards of UPR to around 2-2.5 in the eastern part of the UPR. The detail contour of the thickness of the UPR is available in Singh (1996). As per Singh (1996) throughout the UPR, the top few meters of the succession show a distinctive fining
upward sequence, mostly terminating in mud rich sediments. The Himalaya derived gravel beds are present in the Bhabar and Terai belt; the gravel horizons of central and Alluvial plain reworked Kaankar and carbonated-cemented sand. The gravel in the southern part is derived from peninsular craton.

Additionally, the UPR that runs parallel to the seismically active Himalayan Belt is under high risk of seismic hazard. Apart from the seismicity of the Himalayan Belt, the floor of the UPR trough is corrugated by inequalities and buried ridges. The geophysical information regarding the UPR shows the distinct features of the basement rock. The metamorphic basement reveals that many ridges and basins have high variability in the thickness of sediments (Singh, 1996). The important basement highs are the Delhi-Hardwar ridge, the Faizabad ridge and a poorly developed high in Mirzapur-Ghaziipur area. The southern part of the UPR shows E-W and ENE-WSW trending linear magnetic anomaly zones. Seismic studies in Ganga Plains indicate that the basin and ridges were also active during deposition of Late Proterozoic sediments. The vertical upliftment along the Delhi-Hardwar ridge results in incision of major drainages in the western part of the Ganga Basin. Rao (1973) recognized E-W and ENE-ESW trending active lineaments in the eastern part of the Ganga basin. In this region, there are many E-W trending gravity faults, running parallel to the Ganga region within the narrow zone. Gupta (2006) described the Uttar Pradesh Region (part of Indo-Gangetic Basin) as moderately active when compared to the Himalayas, and considered strike slip faults to be the major cause of earthquakes in the region. Figure 1 also shows major faults, along with the most devastating earthquakes that have shaken the UPR.

3. MULTICHANNEL ANALYSIS OF SURFACE WAVES

Multichannel Analysis of Surface Waves (MASW) is a seismic surface wave geophysical method that records Rayleigh waves on a multichannel record. MASW has been widely used throughout the world for seismic site classification and site response studies. It consists of two methods namely active survey and passive survey. The active MASW method generates surface waves actively through an impact source like a sledgehammer, whereas the passive method utilizes surface waves generated passively by cultural (e.g., traffic) or natural (e.g., thunder and tidal motion) activities. The entire process classically used to produce a $V_s$ profile through spectral analysis of surface waves that
involves three steps: acquisition of ground roll, construction of dispersion curve (a plot of phase velocity versus frequency), and back-calculation (inversion) of the \( V_s \) profile from the calculated dispersion curve.

For this study, active and passive surveys have been carried out at different locations in UPR using 2 Hz geophones. Test setup consists of 24 channel Geode seismographs in combination with 24 vertical geophones with the frequency of 2.0 Hz. In the case of the active survey, an impulsive source of 15-pound sledgehammer striking against a 30-cm x 30-cm size steel plate generates surface waves. However, to increase the investigation depth by several hundreds of meters, the high energy is needed to gain a few more Hz at the low-frequency end of a dispersion curve. Hence, passive surface waves generated from cultural (e.g., traffic) sources are usually of a low-frequency (1–30 Hz) nature with wavelengths ranging from a few km (natural sources) to a few tens (or hundreds) of meters (cultural sources), providing a wide range of penetration depths.

For obtaining the passive data, a passive roadside acquisition method by taking advantage of moving traffic for producing low frequency ambient noise. Park and Miller (2008) recommended that when performing a roadside surface wave survey using a linear receiver array, a 2-D dispersion analysis scheme that accounts for the offline nature of the passive surface waves need to be used. After acquiring the data using both active and passive MASW survey, the individual dispersion curves have been extracted from velocity–frequency diagram (typically shown as figure 2 (a)).

It is often useful or necessary to combine dispersion images processed from active and passive data sets for two reasons: (1) to enlarge the analyzable frequency (therefore depth) ranges of dispersion and (2) to better identify the modal nature of dispersion trends. Hence, combining the active and passive dispersion image has also studied to quantify the depth corresponding to both lower and upper frequency range. Figure 2 shows a typical dispersion curve and shear wave velocity profile for combined active and passive survey obtained from the field study.

\[
V_{530} = \frac{30}{\sum_{i=1}^{n} \frac{1}{V_{5i}}} \quad (1)
\]

4. DYNAMIC ROCK/SOIL MODEL

For representing the variation in small-strain soil/rock stiffness in the UPR, 75 profiles are used. Various researchers (Idriss, 1990; Boore et al., 1994 etc.) noted the significance of small-strain representation by shear modulus and shear wave velocity on the dynamic behavior of soil. As per Dobry et al. (2000), the complete characterization of small strain \( V_s \) from the ground surface down to the bedrock is often not economically feasible; the time-averaged \( V_s \) in the upper 30 m depth (\( V_{530} \)) has been adopted for seismic site classification. The value of \( V_{530} \) is computed using
where, \( H_l, V_{Sl} \) and \( m \) respectively represents the thickness of a layer \( i \), shear wave velocity of layer \( i \) and number of layers in the top 30 m of soil. The sites have been classified as per National Hazard Reduction program (NEHRP, BSSC, 2003). Profiles with \( V_{s30} > 1500 \) m/s, \( 760 < V_{s30} \leq 1500 \) m/s, \( 360 < V_{s30} \leq 760 \) m/s, \( 180 < V_{s30} \leq 360 \) m/s and \( V_{s30} < 180 \) m/s respectively correspond to Site class A, B, C, D and E.

Out of 75 shear wave velocity profiles, around 30% and 40 % is of site class C and D respectively and 20% is of site class B and 10 % is of site class E. Figure 3 shows the representative shear wave velocity profile for site class B, C, D and E obtained from the field study. Based on the statistical analysis of the different profiles it has seen that average standard deviation (\( \sigma \)) is in the range of 0.15-0.25 in the logarithm scale.

Over the years, several researchers have presented the different shear modulus and damping ratio values with shear strain for different materials. Out of all the available modulus reduction and damping curves for different soil types from existing literature, a set of curves are popularly used in the site response analysis. Widely used shear modulus and damping curves were developed by Seed and Idriss (1970), EPRI (1993), Vucetic and Dobry (1991), Ishibashi and Zhang (1993), Seed et al. (1986), Sun et al. (1988) and many more for representing the dynamic behaviour of the soil column. Hardin and Drnevich (1972), Kokusho (1980) and several other researchers recognized the effect of confining pressure on dynamic soil properties as the most significant for granular profiles.

In this study, the normalized shear modulus (\( G/G_{max} \)) and material damping ratio (\( D \)) developed by Zhang et al. (2005, 2008) has been used. Zhang et al. (2005) highlighted that strain (\( \gamma \)), mean effective confining stress (\( \sigma_{m} \)), soil type and plasticity index (PI) are the most important factors that affect the ratio of shear modulus (\( G/G_{max} \)). Sample \( G/G_{max} \) and \( D \) versus strain is given as Figure 4 for effective confining stress of 300 kPa and 1400 kPa for sand and clay (PI = 50%). For the half-space with \( V_{s30} \geq 760 \) m/s, purely linear relationship for \( G/G_{max} \) and \( D \) is assumed as per Aboye et al. (2013)

5. GROUND MOTION DATABASE

The input ground motion is the prerequisite for any site response study. Hence, in this study, the ground motions are selected from both globally and locally available recorded ground motion database. Globally recorded ground motion is taken from Pacific Earthquake Engineering Research database. Locally, recorded ground motions are collected from COSMOS (Consortium of
Organization for Strong Motion Observation Systems) and PESMOS (Program for excellence in strong motion studies) database. All the recorded ground motions have been processed based on Boore (2005). The details regarding the processing these ground motions are also available in Bajaj et al. (2017).

For estimating the input ground motion, seismicity of the whole UPR has been studied. The whole area, shown in Figure 1 is divided into the grid size of 0.5° by 0.5°. Studying the local seismicity and developed probabilistic seismic hazard map around the site of measured shear wave velocity, it has concluded that hazard is dominated by the event with magnitude range ($M_w$) form 6 to 9 and distance ($R$) from 10 to 35 km. The range has been selected using the deaggregation of the seismic hazard for a return period of 2475 years. Hence the recorded ground motion is selected for a particular site considering local seismicity.

As the recorded ground motions for the Himalayan region are available only after 1986, hence the globally available strong motion database is also used to study the local site effect for the deep profiles in UPR. Recorded strong ground motions such as 1940 El-Centro, 1985 Mexico, 1989 Loma Prieta, 1994 Northridge, 1995 Hyogoken Nanbu and 1999 Chi-Chi etc. have been used in many of the site response studies in India. These ground motions were either used directly or scaled as per required peak ground acceleration (PGA) value. The other important factor while selecting the ground motions are its characteristics which controls the response of the soil column. These characteristics are frequency content, duration and amplitude of the ground motion. As local seismicity or seismic hazard analysis would only give the PGA at bedrock which would be only useful for determining amplitude while selecting ground motion. Therefore, seismicity alone would not be used for selecting the input ground motion for site response studies. Hence, in this study, the details regarding the fourier amplitude spectrum (FAS) which corresponding source, site and path parameter has also studied, while selecting the ground motion. Based on Bajaj et al. (2017), the ground motion matches well with the region specific FAS and duration parameter has also considered in determining the local site effect. For a particular site, multiple ground motion are used for non-linear site response analysis. In that way uncertainty in the ground motion selection has reduced. Hence the ground motion for a site contains both near-site and far-site ground motions.

6. SITE RESPONSE ANALYSIS

Site response analysis is often used to estimate the ground motion characteristics at the surface of the soil column. For important projects, site-specific data is used to perform detailed site response analysis for the site, for which the wave propagation equation is solved for a site condition and ground motion. In actual practice, only the one-dimensional (1D) wave propagation equation is usually solved as evident with the existence of various site response software such as Shake91, DEEPSOIL, EERA, STRATA. The computer program DEEPSOIL (Hashash et al., 2016) is used to perform 1D total stress ground response analysis. The 1D assumption is taken to be valid for two reasons. First, because of
subsequent refractions by the soil layers, stress waves propagate from the earthquake focus to the earth’s surface in a nearly vertical path, especially close to the surface (Aboye et al., 2013). Second, soil properties generally vary more rapidly in the vertical direction than in the horizontal direction, making the vertical soil/rock column more important. The stated justifications are made by not taking the topography of the bedrock or earthquake directivity effects into account, which are not well established for UPR. The detail regarding the algorithm used in DEEPSOIL can be referred from Hashash et al. (2010, 2015, 2016). In this study, the formulation by Hashash et al. (2016) is used to obtain estimates of shear strength. Frequency independent rayleigh damping is used to model the small strain damping as suggested by Phillips and Hashash (2009). Dependence of overburden pressure on the behavior of the modulus reduction curve and small strain damping is modeled through two coefficients in DEEPSOIL.

7. ASSESSMENT OF SITE AMPLIFICATION

Time histories obtained from ground response analyses can be used directly to represent ground surface motions. For determining the surface response, either synthetic time-histories can be derived to match the desired design ground surface response spectrum (U.S. Army Corps of Engineers 1999) or recorded motions can be scaled or modified to match the desired target spectrum. Generally, the direct use of response spectra calculated from the surface motions is not preferred in practice. However, it is advantageous and well accepted to obtain site amplification ratio from the ground response analyses. The site amplification factor is the ratio between equivalent measures of ground surface motion intensity and the intensity of corresponding input rock motion i.e.

\[
AF = \frac{IM_{Soil}}{IM_{Rock}}
\]

Where, IM and AF, respectively the intensity measure and amplification factor.

For the site response analysis of the deep UPR, firstly 2015, Nepal earthquake is given as the input time history at bedrock level, which is considered as the layer having \( V_{S30} = 760 \) m/s to determine the amplification factor for the representative site and given in Figure 3. The used input ground motion is recorded at KATNP station, which is at an epicentral distance of 59.9 km and the recorded PGA of 0.163 g. The variation of PGA value along the depth for all the representative sites is given as Figure 5. For site class E, amplification is more as compare to the other site class for the same ground motion.

Variation of amplification factor with PGA value for different site class is also studied. As stated above, for a site, multiple ground motions are used based on amplitude, frequency content and duration. Hence, variation of amplification factor with PGA is also studied. A typical example of variation of amplification factor with PGA for representative site class D (see Figure 3) is given as Figure 6. The variation amplification factors with PGA obtained from the present study is compared with the EPRI (1993), Ashford et al. (2000) and Kumar et al. (2016). It can be seen from Figure 6 that for lower PGA the outcome obtained from present study is matching well with the Kumar et al. (2016). A high value of amplification factor for low value of PGA is observed (See Figure 6). As per Romero and Rix (2005), large amplifications corresponding to low amplitude ground motions were observed during 1989 Loma Prieta EQ and 1985 Michoacan EQ. Large PGA are the attributes of large strains and at large strains, the soil response is dominated by large damping values. Due to large damping ratios, relatively low amplification factors are observed for input motions having large PGA.
Further, all the shear wave velocity profiles are used for calculating the amplification factor. As explained above for a site different ground motion are used to put the variability in ground motion characteristics. A typical example of the variation of the amplification factor with depth for site class B is given as Figure 7. For all the sites that are classified as site class B, different input ground motions are used. In Figure 7, the mean of the amplification factor obtained by using 2015 Nepal earthquake (0.163g, 7.8 Mw, 59.9 km), 1999 ChiChi earthquake (0.183g, 7.6 Mw, 15.29 km), 1979 Imperial Valley earthquake (0.169g, 6.5 Mw, 26.5 km), 1994 Northridge earthquake (0.217g, 6.7 Mw, 26.8 km) and 1966 Parkfield earthquake (0.357g, 6.1 Mw, 9.9 km) applied to all the sites is also given. The solid black lines represent the mean of the amplification factor obtained from above mentioned strong ground motion. The light lines represent the mean of the amplification factor obtained at different site class by inputting the multiple ground motions. It can be seen from Figure 7 that different ground motions have different impact on the amplification factor. For example, for the same sites, 2015 Nepal earthquake is giving different amplification factor than 1979 Imperial Valley earthquake. This is because of the change in the characteristic of the ground motion. Hence, from Figure 7, it can be concluded that for the determination of the amplification factor of the deep soil profiles, characteristic of the ground motion i.e. frequency content, duration and amplitude has a large impact on first 80 m of the soil column.

Based on the analysis, it has seen that for site class E, the range of amplification factor at the surface is 1.5 to 3.82 using randomly selected ground motions and from 2.35 to 7.58 using Site-specific ground motion as input. The used randomly selected ground motions have a similar distribution of amplitudes as of Site-specific ground motion. Similarly, a difference of around 30 to 35% is also observed in the case of site class D and C. Based on the analysis, it has determined that for the amplification range of site class E, D, C and B is 2.35 to 7.58, 1.82 to 5.58, 1.5 to 4.92 and 1.23 to 3.25 respectively in case of PGA.
Further, the response spectra obtained from the site response analysis for different site at the surface is compared and dominant period has been studied. A typical example of the response spectra obtained at the surface and bedrock for site class B is given as Figure 8. The dotted grey lines represent the mean spectral acceleration (SA) at different period for different sites. The mean SA is calculated by using different input motion at the same site that is explained above. The solid blue and black line represents the mean SA at the bedrock and surface, these are further used for calculating the amplification factor corresponding to different sites.

Further, the amplification factor at different periods has been determined for different site class. The average amplification factor for the different site class is given as Figure 9. It has seen that for deep sites corresponding to site class B, C, D and E respectively amplified between the period 0.2 to 0.3 s, 0.8 to 1 s, 2 to 3 s and above 5 s.

8. CONCLUSIONS

Site response is indispensable as it controls the damage scenario during an earthquake. The extent of damages at any site is not only the function of earthquake magnitude and its distance from the epicenter but also the subsoil characteristics at the site. The response of shallow and deep soil columns is also different for the same intensity of earthquakes. In this study, an attempt has been made to determine the amplification factor of the deep soil sites in the Uttar Pradesh Region. Firstly, the shear wave velocity up to 200 m depth has been determined based on the geophysical test named multichannel analysis of the shear wave. Further, these sites were classified based on time-averaged $V_s$ in the upper 30 m depth as per NEHRP (BSSC,2003). The obtained $V_s$ profiles were further used to estimate the site-specific response parameters at different locations by carrying out non-linear site response analysis. The input ground motions for site response analysis selected considering seismicity and availability. Based on the analysis, it was seen that for site class E, the range of amplification factor at the surface is 1.5 to 3.82 using randomly selected ground motions and from 2.35 to 7.58 using Site-specific ground motion as input. Similarly, difference of around 30 to 35% is also observed in case of site class D and C. Based on the analysis, it has determined that for the amplification range of site class E, D, C and B is 2.35 to 7.58, 1.82 to 5.58, 1.5 to 4.92 and 1.23 to 3.25 respectively.
Figure 8. A typical example of the response spectra for site class B showing its mean at the surface and bedrock.

Figure 9. Showing the comparison of amplification factor for different spectral period for seismic site class B, C, D and E

9. REFERENCES


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.


Romero SM, Rix GJ (2005). Ground motion amplification of soils in the upper Mississippi embayment. Report no. GIT-CEE/GEO-01-1, National Science Foundation Mid America Earthquake Center


