Evaluation of site-specific characteristics using microtremor measurements in the Gorakhpur city of Uttar Pradesh, India

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The microtremor measurements are carried out in and around the Gorakhpur city (Uttar Pradesh), India, overlain by alluvium at about 150 sites to understand the local site conditions. Horizontal-to-vertical spectral ratio (HVSR) confirms that the majority of sites have a predominant frequency of ~0.45 Hz, which may suggest the prevalence of thick soft sediments in the area. Conspicuously, a number of multiple peaks in HVSR curves at few sites may reflect the presence of different interfaces with significant impedance contrasts. Maximum amplification is observed of 4.0–5.3 to the NW–SE of the city, whilst few sites in the city are found to be associated with different values of peak amplification factor that varied between 2.0 and 4.0. It is also observed that the ground vulnerability index ($K_g$) in Gorakhpur city has values higher than 10.0 at most of the sites. Assimilation of 1-D velocity model for the city clearly shows that low shear wave velocity (~300 m/s) down to the depth of ~35 m, suggesting thick piles of sediments that may correspond to fluvial river system in the area, whilst the peak frequency of about 0.45 Hz may correspond to the Quaternary–Tertiary sediment boundary that may exist at deeper layers (~1000 m). The inference of this study may be used as inputs for earthquake risk management by reducing the severity of earthquake shaking through design of earthquake risk resilient structures.

Keywords. Site characterization; microtremor; H/V spectral ratio; amplification; shear wave velocity; Gorakhpur.

1. Introduction

The Gorakhpur city of Uttar Pradesh, India is located on a river fluvial system of vast Indo-Gangetic plain having a total population of 0.673 million, as per the recent census of India (Census of India 2011). This city is developing very fast in length and breadth with new infrastructure and industrialization. It is the second largest populated city after Varanasi in east Uttar Pradesh, India. Topography of the city is largely plain, average height is 80 m from mean sea level (Verma 2009). The height ranges from north 95 m to south 72 m near Ramgarh Taal situated in the southeast of the city. The study region falls in seismic zone III of the seismic zonation map of India (BIS 1893 (Part 1)). Since the study region lies close to the most seismically active Himalayan belt in India, it makes the city more vulnerable. Several sets of studies in the Himalayan arc, since years unravelled the fact that there exist seismic gaps where there are no evidence of occurrences of mega
disastrous earthquakes in recent years (Bilham et al. 1997, 2001; Bilham 2004; Bilham and Ambraseys 2005; Gupta and Gahalaut 2015; Mishra 2020). They argued that the number of smaller earthquakes are not good enough to release the stress accumulated over the years and that the likelihood of an earthquake with magnitude $\geq 8.0$ was serious. It is, however, the leakage of stress in the seismic gap zones due to micro-to-moderate earthquakes may prohibit the accumulation of much strain energy for making greater and destructive earthquakes. Those earthquakes may impact cities, which are located over the soft soils in Gangetic alluvial plain among which Gorakhpur, Varanasi, Allahabad, Mirzapur, Azamgarh, Jaunpur, Ballia and many more are important cities, which are found to be more vulnerable due to earthquake shaking (figure 1). These districts in the Uttar Pradesh state falls in seismic Zone III, and were considered safe zone before Nepal earthquake in April 2015 (BIS 1893 (Part 1)). The Gorakhpur and surrounding districts of Uttar Pradesh are close to the Himalayan seismic belt and the region has witnessed many minor-to-major destructive earthquakes in the past. For the first time, an attempt was made to investigate the city of Gorakhpur using microtremor surveys under a pilot project sponsored by the Ministry of Earth Sciences to establish the efficacy of the site response study for the area.

The site effect studies on the basis of spectral ratio analysis of microtremor measurements have been developed since the 1985 Mexico earthquake. Later microtremor data have been used extensively to characterize the site properties of different metropolitan cities and seismicity-prone cities in the country (e.g., Bard 1998; Mukhopadhyay et al. 2002; Nath et al. 2003, 2015; Mukhopadhyay and Bormann 2004; Mandal et al. 2005; Parvez and Madhukar 2006; Cara et al. 2008; Walling et al. 2009; Surve and Mohan 2010; Rastogi et al. 2011; Sukumaran et al. 2011; Hellel et al. 2012; Anbazhagan et al. 2013; Singh et al. 2014a, b, 2017a, b, 2019; Singh 2015; Shankar et al. 2021). Microtremor measurements are non-destructive, fast, robust and cost-effective for the study of soil site characterization and local geology of shallow subsurface structures. Microtremors are low amplitude ambient vibration or noise of ground caused by natural phenomena such as ocean–land interaction, atmospheric disturbance and man-made anthropogenic noises such as traffic, cattle movement in groups, industrial noise, etc. (Hardesty 2008; Ardhuin et al. 2019). Observation of microtremor data gives useful information on dynamic property of local site characteristics such as predominant frequency, amplification, sub-shallow structure and ground liquefaction vulnerability (Bard 1998; Parolai et al. 2002, 2010; Wathelet et al. 2004; Singh et al. 2017b, 2019).

The enhanced seismicity in and around the study region warrants assessment of seismic hazards to aid engineers in urban developments. The Gorakhpur city is fast growing with high-density population where many multi-storey buildings had come up during the past few years and trends are increasing day-by-day, which exerts tremendous pressure on the limited land resources. Apart from building towers, important engineering structures like Metro rail and new shopping malls are proposed. Recently, Government of India announced to develop Gorakhpur city under smart city category. In order to understand the spatial distribution of susceptible zones and to delineate them,
closely spaced ground shaking site effects data are necessary for site-specific response investigations and the preparation of seismic hazard microzonation map for the city. This map would be useful to take precautionary steps in future construction and developmental activities. The effect of a large earthquake close to a city can cause not only a large number of causalities, but also economic collapse. This time, the impact of tremors from Nepal was not so aggressive in Uttar Pradesh, India. It was the alluvium cover in the Indo-Gangetic plain, which acted as a cushion and prevented large-scale damage in the state. In geological terms, the state falls in the safe zone as the alluvium cover acts as a shock absorber. However, faults or cracks in the rocky surface below the alluvium cover could have been activated by the high magnitude of tremors. The rocky surface below the alluvium cover of the Indo-Gangetic plain has a thickness of about 2.5 km and around the Himalayan foothills its thickness increases to around 4 km (Srinivas et al. 2012). Emphasis should be on ensuring that high-rise buildings are earthquake resistant. In view of this, an attempt is made to estimate the local site condition in Gorakhpur city, which is important for seismic hazard analysis.

2. Geological settings

As mentioned above, the city of Gorakhpur is situated in Indo-Gangetic plain on the bank of Rapti river in Ganga basin which is associated with different fan sediment of varying shape and size gets deposited during the flow of Rapti and Ghaghara rivers in the west of the city. Gandak river in the east of the city also flows from northwest to southeast direction adjacent to the city (figure 1). The source of sediments embodies with sands and clay load carried and transported by river from Himalaya as well as with the weathering and erosion of peninsula craton of Vindhyan rocks (Shukla et al. 2008). The recent deposits characterize as quaternary consist of younger to older alluvial comprises fine to coarse sand, silt and clay. In soft soil, seismic energy gets trapped and leading to amplification of vibration may cause destruction to man-made structures. Therefore, it is important to know that resonance frequency and amplification of alluvial soil deposits and engineering bed layer (EBL) depth.

3. Data and methodology

The measurements of the microtremor from natural sources were carried out mostly for an hour at each site in the early morning to avoid anthropogenic noises. Longer duration data also acquired at few sites to understand the effect of temporal variability on the spectral curves. A set of seismometers with digital recorders are deployed at each site to collect the data. GEObit sensor coupled with a SRi32S digitizer deployed at each site. Each recording system is equipped with an internal 24-bit digitizer and an external GPS receiver to allow precise synchronization of the measurements. GEObit has a flat frequency response from 10 s to 98 Hz with sensitivity 1500 V/m/sec. This sensor (10s) can be well appropriate for these purposes and for local site effect studies that utilize the H/V ratio technique, thanks also to its low weight and easy transportability. Conversely, the broadband seismometers, with natural period higher than 20s, are not recommended because they require a long stabilization time.

Array measurements of microtremors were carried out at a site in the campus of Madan Mohan Malviya Technical University within the city of Gorakhpur in the west (figure 3) during December 2019. The measurements at the site were taken using triangular arrays which consist of three recording stations on the circumference of the circle and one in the centre of the circle (figure 8a). The recording duration at the site was 120 min, at the sampling rate of 100 samples/sec and standard frequency band from 0.1 to 98 Hz in order to get the period bandwidths adequate to explore shear wave velocity. For array measurement, R is the distance between the central and outer stations, and distance between two outer stations (30 m) used for better resolution. However, considering the large thickness of sediments in the city, further large arrays are required to get the information in deeper layers. The small array can be useful to extract information about the uppermost layers, while through the large array it is aimed to determine the depth of the bedrock or at least the depth of the lowermost hard soil formation.

In order to establish the perfect geometry of the array, it is necessary to measure the distance as precisely possible between stations in the field. The Electronic Digital Meter (EDM) has been used to estimate the distances of the different pair of stations as shown in figure 8(a). The principle of EDM is based on the ejecting laser beam to a target plate
which gives the distance precise in cm. Once the places for all the stations are marked and seismometers are fixed, then start the data acquisition for at least two hours. Various methods are applied to understand the local site conditions in Gorakhpur city. The details of the methodology are given below as:

3.1 H/V spectral ratio

Horizontal-to-vertical spectral ratio (HVSR) applied based on the characterization of soil layers (Nogoshi and Igarashi 1970), which later extended using seismological records of ambient noise by Nakamura (1989) to understand the local site conditions and characterize the response. The concept of Nakamura (1989) has been used by different researchers for different study areas that proved an efficient tool for building earthquake risk resilient structures and infrastructures (Mishra 2020; Mishra et al. 2020). Various tests were performed with different parameters to avoid misinterpretation and to quantify the significance of microtremor contribution to local site conditions. Microtremor data were processed with the help of Sesarray software (www.geopsy.org). In this approach, the baseline correction is first performed to correct the ground motion time series, prior to correcting the data for the instrument response. Less spiky data are selected, as shown in figure 2. The three-component ground motion time series recorded at a station in the Gorakhpur city corrected for instrumental response is shown in figure 2. A band-pass filter in the frequency range of 0.1–20 Hz applied on the selected and scrutinized data. The following steps are performed on the filtered data: (i) The filtered data is to be subdivided into smaller windows of time length 20 sec each with 50% overlapping, (ii) each window is 5% cosine tapered and transformed into the Fourier domain, (iii) raw Fourier spectra have oscillations and spikes which lead to unusual H/V ratios, (iv) to overcome such problem, each spectrum is smoothed prior to the calculation of the H/V spectral ratio, using Konno–Ohmachi smoothing technique for a bandwidth coefficient, as $b$ value of 40, (v) the instrumental response correction was carried out, (vi) finally, all the windowed spectra are averaged to obtain V, N and E spectra. Therefore, the H/V spectral ratio is calculated by dividing the root mean square of the horizontal components (N and E) with the vertical component (V).

3.2 Vulnerability index or liquefaction potential

Vulnerability index has been proposed by Nakamura (1996) for accurately estimating damage by an earthquake on surface ground structure. The ground vulnerability index $(K_g)$ values in the liquefied areas are found to be higher than those in the adjacent areas devoid of liquefaction. From these observations, it is reasonable to conclude that the value of $K_g$ maybe considered for predicting the potential for soil liquefaction at the site. It is defined as:

$$K_g = \frac{A_f^2}{f_0}$$

where, $f_0$ is the predominant frequency and $A_f$ is the peak amplitude at peak frequency $f_0$.

Recent review on seismic microzonation by Mishra et al. (2020) shed important light on estimates of site vulnerability that reflect the combined effect of peak amplification and predominant frequency estimating vulnerability index.

3.3 Spatial auto-correlation (SPAC) method

The SPAC method applied to estimate the shallow subsurface structure in the city. The spatial auto-correlation techniques take the advantage of the random distribution of sources in time and space to link auto-correlation ratios to phase velocities. In the case of a single-valued phase velocity per frequency band, Aki (1957) demonstrated that these
ratios have the shape of Bessel functions of zero order, the argument of which is dependent upon the dispersion curve values and array aperture. The spatial auto-correlation function between two sensors is defined by (Aki 1957)

\[ \phi(\xi) = \frac{1}{T} \int_0^T u_0(t)v_\xi(t)dt \quad (1) \]

where \( u_0 \) and \( v_\xi \) are the signals recorded during \( T \) seconds at two stations separated by a distance \( \xi \). If the signals are filtered with a narrow frequency band around \( \omega_0 \), the autocorrelation ratios defined by

\[ \rho(\xi, \omega_0) = \frac{\phi(\xi, \omega_0)}{\phi(0, \omega_0)} \quad (2) \]

are calculated for all pairs of receivers. For a given inter-distance \( \xi \), Aki (1957) demonstrated that the azimuthally average of \( \rho(\xi, \omega_0) \) has the shape of Bessel functions

\[ \overline{\rho(\xi, \omega_0)} = J_0 \left( \frac{\alpha_0}{c(\omega_0)} \right) \quad (3) \]

where \( J_0 \) is the Bessel function of the first order and \( c(\omega_0) \) is the dispersion curve, equation (1) is computed in the time domain on filtered signals (a
taper in the frequency domain is used to ensure a zero-phase filter. Like for the f–k method, the raw signals are divided into smaller time windows on which the auto-correlation ratios are computed. Consequently, for each frequency band, for each range of inter-distance and for each individual time window, an azimuthally averaged auto-correlation ratio is calculated and the phase velocity \( c \) is calculated from equation (2) via the Bessel function. Here, it should be noteworthy that the spatial auto-correlation function defined in equation (2) is a characteristic quantity of the site where the arrays are deployed.

As inversion tool is able to infer subsurface structure in most of geophysical methods. The dispersion is also known as auto-correlation curve to determine the shear wave profile up to a depth of 30 m. Several inversion methods of common use in geophysics are available, however, the neighbourhood algorithm (Sambridge 1999) has been chosen as dispersion curve inversion in this study. In the neighbourhood algorithm, a random walk technique is performed with a uniform probability density function inside the cell and zero probability outside. A walk is nothing but a sequence of perturbation to a model along all axis. The modified model is statistically independent of the original model. The samples produced by random walk will be uniformly distributed inside the cell without care geometry of cell. To confine the random walk within a cell, it is necessary to calculate the multi-dimensional limits of the cell. Sambridge (1999) proposed an original algorithm to compute only the limits along lines, which are parallel to the axis, in precise and efficient way. These lines are supportive to successive segments of the random walks. The neighbourhood algorithm like all other Monte Carlo techniques relies on a quasi or pseudo random generator. If two models are generated by different processes can be merged to construct a

Figure 4. H/V curves along with azimuth vs. frequency plot at various sites in and around Gorakhpur city. Plot of H/V ratio average value with solid line and dotted lines indicate standard deviations. Station location is shown in figure 3 with black dots.
more reliable model refined approximation of the misfit function. The models obtained from the neighbourhood algorithm do not have the same statistical properties as the posterior probability density. If a large number of iterations are performed close to best-fit model. That means re-sampling of the parameter space and compare the probability density with misfit function, calculated misfit value is the distance between a calculated dispersion curve and experimental curve. The misfit is calculated based on Sambridge (1999) method.

4. Results and discussion

Microtremor data recorded at 150 sites in the city are analysed to understand the local site conditions. The results are presented in figure 3. The spectral ratios are presented in the frequency range of 0.2–15 Hz, which is the range of interest for common civil engineering structures. These H/V response in figure 4(a–e) shows the study area from north to south, east to west and central portion, position is shown in figure 3 with black dots. Most of the sites have shown a fundamental resonance frequency at 0.45 ± 0.01 Hz except very few sites, which show predominant frequency ~1.44 ± 0.02 Hz (figure 4d). In the city area, the predominant frequencies mostly vary from 0.38 to 0.48 Hz (figure 5). Secondary peaks ($f_1$) were observed at 34 stations located mostly in the western and eastern parts of the city. The $f_1$ peaks show a smooth bump between 4.0 and 6.0 Hz.

The dispersion curve, derived from microtremor array measurement (MAM) observations at the
site in west of Gorakhpur city, shows good measurements between 1.0 and 6.0 Hz in a phase-slowness range of 0.005–0.0004 s/m (figure 8c). The phase slowness increases as the frequency increases (figure 8c). The inverted $V_s$ profiles shown with misfit values in figure 8(d), explain local site effects in the city. $V_s$ is better retrieved than $V_p$ because the Rayleigh dispersion curve is more sensitive to $V_s$ than $V_p$. The $V_s$ model that best explains the dispersion curve is characterized by a 35.0-m thick first layer with a $V_s \sim 300$ m/s. Below this layer, the estimated $V_s$ profile shows a 60 m thick sedimentary layer with $V_s$ of about 1200 m/s (figure 8d). This indicates a remarkable difference in soil structure. Indeed, the sediments (soft and compact) in this region are more than 4 km is delineated through seismological studies using broadband seismometer and the dominant frequency is about 0.14 Hz determined from the Gorkha earthquake sequence in the Indo-Gangetic plain (Srinagesh et al. 2011).

The variations in the HVSR peaks at different frequencies were reflected in the undulations of sediments deposition. The frequency $>1.0$ Hz is located in a very small area, which is the west part of Ramgarh Taal near Taramandal area. The presence of such peaks in the HVSR curve is indicative of an impedance contrast between the superficial soft layers and the underlying hard rock. Large peak values are generally associated with sharp contrasts that are likely to amplify ground motion (Parolai et al. 2002; Sukumaran et al., 2011; Singh 2015; Singh et al. 2017b). At some sites, the HVSR curves show plateau-like shape. This could be because of the topography causing variations in soil thickness and changes in younger alluvial to older alluvial deposits or could be liquefaction. Hence, the resonance frequency varies inversely with basement depth, as expected. This shows that even if the basement depths were not known, we could use the variations in resonance frequency to make some inferences.

Spatial distribution of predominant frequency and corresponding amplitude maps are presented after processing of microtremor data in figures 5 and 6, respectively. Subsequently, the spatial
distribution of liquefaction vulnerability index \((K_g)\) values (figure 7). The amplification values are varied between \(\sim 2.5\) and \(\sim 5.3\) and resemble the change in the predominant frequency ranges from \(\sim 0.4\) to \(\sim 1.5\) Hz. The presence of large amplification could be related to a high impedance contrast between the sedimentary layers (Bard 1998; Rastogi et al. 2011; Singh 2015; Dewangan et al. 2017; Singh et al. 2017b). A low amplification could be related to a smaller contrast, indicating the presence of hard rock (Bonnefoy-Claudet et al. 2006; Singh et al. 2017b). The map shows that the amplification in the northern parts is higher compared to the central part of the city. On the other hand, the eastern, western and southern parts of the city show moderate amplification. In particular, the western part of the Ramgarh Taal has slightly higher values of \(f_0\), which is up to 1.498 Hz. The \(f_1\) peaks as resulting from the resonance of the shallower impedance contrast such as recent alluvium and old alluvium.

In order to reasonably ascertain the limits of the spatial variations, an adjustable tension used for continuous-curvature surface gridding algorithm allows us to obtain a smooth field of the parameters as shown in figures 5–7. In general, the parameters vary slightly in space without large difference between neighbouring sites. Towards the northern parts of the city, the amplification varies within a narrow range of 3.7–5.3 and southeastern part variation ranges from 3.3 to 5.3 (figure 6). The lowest variation in amplification was observed in the central part of the city in the range of 2.52–3.08, which is attributed to relatively consolidated soils (figure 6). Relatively lower amplifications and higher predominant frequencies are observed in a pocket west of Ramgarh Taal. This behaviour could be explained by thin sedimentary cover with low impedance contrast at the contact with the bedrock. Nakamura (1996) proposed the liquefaction vulnerability index \((K_g)\) to quantify the vulnerability of soil towards liquefaction. It can be seen from figure 7 that the \(K_g\) value varies from 13.96 to 68.42. Higher \(K_g\) values which are greater than 10 are observed in the study area which shows lower predominant frequencies and higher amplitude, in conformity with the larger \(K_g\) values (Singh et al. 2017b). Various studies have already been carried out to demonstrate that sites with \(K_g\) values are greater than or equal to 10 experience liquefaction during large earthquakes (e.g., Nakamura 1996, 1997; Huang and Tseng 2002; Saita et al. 2004; Beroya et al. 2009; Singh et al. 2017b). The estimates of \(K_g\) obtained in this study indicate that Gorakhpur city has potential damage due to liquefaction. Therefore, the \(K_g\) values provide important information about site conditions that can be used for land-use planning and earthquake hazard mitigation.

5. Conclusions

The microtremor surveys were conducted at 150 locations in and around Gorakhpur city. The average predominant frequencies in the city vary from 0.45 to 0.46 Hz that corresponds to amplification variation from 3.3 to 3.5. The amplification is found to be increased towards the northern part of the city; while, it decreases towards the central part. The estimated results are consistent with the basin topography; where the sediment thickness increases steadily. Dispersion curve shows increasing trend of slowness with increasing frequency. The inverted shear wave velocity shows the uppermost soft sediments (35 m) of shear wave velocity around 300 m/s, which may represent the boundary of Holocene-I and Holocene-II. Further velocity ~1200 m/s down to depth of 100 m indicates the competent basement beneath the city. Estimates of various parameters made for different sites for the city in this study may be used as an input for evolving earthquake risk resilient model for structures and infrastructures to be used for a plan for disaster risk mitigation in Gorakhpur city.

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Author statement

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