Establishing empirical correlation between sediment thickness and resonant frequency using HVSR for the Indo-Gangetic Plain

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In this study, microtremor survey was carried out at 31 locations of Indo-Gangetic Plains (IGP) using a pair of portable three-component short-period seismometers (Guralp CMG-6T-1) and Kelunji Echo Pro digital data acquisition system. The acquired raw data was processed to obtain the average *H*/*V* ratio of the ambient vibration spectrum. The frequency corresponding to the first peak of the average *H*/*V* spectrum was taken as resonant frequency of that particular site. A comparison was made between the resonant frequencies obtained from peak of the *H*/*V* spectrum with those obtained using the source–receiver function from previously published work. The results were in good agreement with each other. An empirical equation has been established for the IGP by relating resonance frequency with sediment thickness, using available data from nearby boreholes drilled up to bedrock. The empirical equation was compared with other equations available for deep soil sites, i.e. sites with soil thickness more than 750 m. Further, a combined equation was developed for the digitized data taken from previously published works of deep soil sites. Finally, it has been found that the region-specific equation gives better estimate of sediment thickness than the other empirical equations; but in absence of such a region-specific equation, the proposed combined equation can be used for a quick preliminary assessment of sediment thickness of a deep soil region.

Keywords: HVSR method, Indo-Gangetic plains, microtremor, resonant frequency, sediment thickness.

DYNAMIC properties of subsurface layers are one of the most critical factors which influence the ground motion characteristics. The seismic waveform at a particular site is almost similar for any earthquake recording because of the influence of the dynamic characteristics of the subsurface layers on the ground motion. In this regard, the Indo-Gangetic Plains (IGP) can be considered to be of particular importance because of its association with the tectonically active Himalayan region and the deep sediments deposited over a long period of time. The deep sediments present in the IGP can cause local site amplification, and in extreme cases may induce a condition of 'resonance' at those sites where the natural frequency of the structure matches with that of the surface ground motion. Also, the deep loose sediments are prone to liquefaction due to seismic events, which could have extensive damage on the structures built in and around the IGP. Hence, an estimation of sediment thickness would be helpful in the preliminary assessment of the dynamic characteristics of the subsurface soil in the IGP.

It has been found that the seismic signals from a hard site are uniform throughout all frequencies, but for a soft soil site the signal is amplified at its resonant frequency, which is a function of soil type, bedrock configuration, etc. Hence, if the source and the path effects were to be removed from the spectra of the signal, then a flat response would be available at a hard rock site, and a maximum amplitude at resonant frequency for a soft soil site. Researchers have used different methods to remove source and path effects[1–9]. A simple method was introduced by Nakamura[10] known as the *H*/*V* ratio method. This method could be used to estimate the site effects, by measuring only the ambient vibrations on the ground surface using single instrument. The site response estimate is obtained by dividing the mean of horizontal component by the vertical component of the noise spectrum. It was observed that the horizontal component of ground motion showed larger amplifications in comparison with the vertical component at the resonant frequency. Hence, horizontal to vertical spectral ratio (HVSR) showed a peak at that particular frequency which corresponded well to the resonant frequency of the soil. This technique has been used worldwide as a cost-effective tool to estimate the resonant frequency of the site by determining the HVSR at a single-station measurement[11].

Several studies are available regarding the estimation of *H*/*V* ratio from the earthquakes and microtremor of various sedimentary plains. Theoretical explanation about *H*/*V* ratio method is available in the literature, e.g. refs 12, 13. *H*/*V* Ratio method finds its application in estimating wave amplification, site effect evaluation, microzonation studies, sediment depth estimation, and in liquefaction studies[13–22]. Some microtremor studies have also been done in India. Dinesh *et al.*[23] used the microtremor *H*/*V*

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ratio measurements to establish an empirical correlation between sediment thickness and resonant frequency for Bangalore city. Sukumaran *et al.*[24] used the microtremor data for calculating HVSR and to compute the approximate thickness Quaternary sediment and late Quaternary–early Tertiary topography for the part of lower reaches of Narmada valley. Natarajan and Rajendran[25,26] used the HVSR technique to estimate site response of Kachchh rift basin over the meizoseismal area of the 2001, M_w 7.6, Bhuj (NW India) earthquake, and determined that site effects were not significant during the 2001 earthquake damage observed in Bhuj. Recently, Sant *et al.*[27] have used the microtremor method for subsurface profiling along Banni Plains and bounding faults in Kachchh, Western India; and Joshi *et al.*[28] have used the microtremor method for subsurface profiling of granite pluton in southern Aravalli, Gujarat, India. But, no such experimental study has been conducted for the Indo-Gangetic region. Hence, the present study was taken up to examine the application of Nakamura technique to estimate the sediment depth in Indo-Gangetic plain, and propose an empirical correlation based on the available subsoil characteristics close to microtremor recording stations. Also, other deep site soil thickness correlations developed globally have been examined for their applicability in the IGP.

Study area

The IGP is one of the deepest sedimentary plains in the world. The plain is composed of alluvium deposited by major rivers like the Ganga, Yamuna, Indus, Brahmaputra and their tributaries. In recent years, there is renewed interest in identifying the subsoil characteristics and dynamic properties of the plains because they are prone to earthquake-induced potential hazards, since IGP is tectonically active. IGP is located to the south of sub-Himalaya and extends up to Aravalli in the west, Satpura and Vindhyan ranges in the south. The origin of Indo-Gangetic basin has been subject of interest since the early 1900s when Burrard[29] published a paper on the origin of Indo-Gangetic trough or Himalayan fore-deep. Sedimentary deposits have been interrupted by longitudinal and transverse faults, thereby generating an uneven configuration of subsurface topography consisting of alternating ridges and depressions. Figure 1 shows the geology of the study area marked along with microtremor survey locations.

Geological and geophysical information about IGP shows distinctive subsurface features. The metamorphic basement of IGP is characterized by a number of ridges and faults over which thick sedimentary covers are present[30]. From south, important ridges are Delhi–Haridwar ridge, Faizabad ridge, a poorly developed Mirzapur–Ghazipur ridge and Monghyr–Saharsa ridge; while Raxaul, Bahraich and Puranpur ridge exists in northern part of the basin. The most important faults are Moradabad faults, Bareilly faults, Lucknow faults, Patna faults and the Malda faults. These faults are considered to be tectonically active, with 1934 and 1988 Bihar–Nepal border earthquakes being associated with them. Other major earthquakes have also occurred from 1965 to 1995 in IGP[31]. Earthquakes within IGP or those in the vicinity of the region can cause considerable damage to structures in the IGP due to local site amplification because of the thick sediment deposit.

Information about the sediment thickness of IGP can be acquired through studies such as gravity, seismic and deep drilling for oil exploration by the Oil and Natural Gas Commission[32]. Exploratory wells beneath the Ganga alluvium[33] have revealed that the depth of Neogene (Siwalik) sediments varies from 500 to 1500 m. In northern part of the basin, deep borehole studies of Shahjahanpur and Bilaspur shows the presence of 4.1 km thick recent alluvial sediments overlying the molassic formations of the Siwalik group[33]. Further south, the thickness of sediments decreased to about 1.2 km at Lucknow and 500–600 m at Kanpur. The comparatively thin sediment thickness in Kanpur and Lucknow than that in Shahjahanpur and Bilaspur is due to the presence of the Faizabad ridge[34]. Sudden increase in basement depth to more than 2.5 km within a profile distance of 20 km was observed in Lucknow which could be attributed to the Lucknow fault[35]. The other notable feature seen is the sudden deepening of the basement depth at Sandilain comparison to Kanpur and Lucknow by more than 1.5 km (ref. 34). The Bundelkhand massif exposed at the southern end of the basin was detected with sediment thickness of 250–300 m (ref. 35).

Microtremor experiments

Microtremor measurements were carried out at 31 locations of IGP using a pair of portable three-component

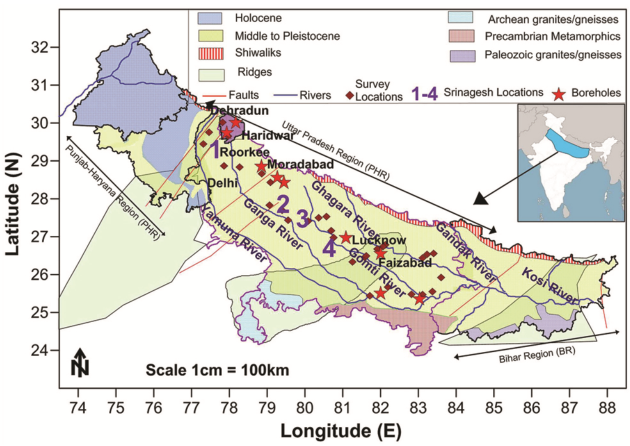

Figure 1. Study area map showing Indo-Gangetic basin with lithology.

Table 1. HVSR resonant frequency of survey locations along with reliability parameters

Location	Latitude (°N)	Longitude (°E)	Number of windows (n_w)	Length of windows (l_w)	Resonant frequency (Hz)	Number of windows and cycles (n_c)	Calculated sediment thickness from eq. (2) (m)
Hussain Ganj Kalan	26.44	81.68	27	60	0.18	291.6	765.44
Allahabad	25.43	81.81	9	60	0.39	210.6	448.97
Dherahi	25.52	83.00	14	60	0.91	764.4	250.21
Sata Hariya	25.66	82.25	17	60	0.22	224.4	666.47
Faizabad I	26.77	82.19	17	60	0.37	377.4	465.58
Faizabad II	26.72	82.13	22	60	0.17	224.4	796.23
Maupara	25.54	83.35	14	60	0.32	268.8	514.63
Mau	25.91	83.56	20	60	0.171	205.2	793.02
Benwapur	26.54	83.38	18	60	0.32	345.6	514.63
Bankati Bujurg	26.52	83.22	13	60	0.44	343.2	413.11
Saneha	26.42	83.11	20	60	0.2	240	711.77
Alinagar	26.48	81.72	16	60	0.385	369.6	452.98
Sijni	26.33	81.39	19	60	0.206	234.8	697.40
Sharakpur	26.96	80.92	16	60	0.33	316.8	503.82
Biswan	27.48	80.97	14	60	0.25	210	610.20
Gopalpur Rampur	27.23	80.68	21	60	0.18	226.8	765.44
Adora	27.66	80.49	15	60	0.31	279	526.03
Bharayal	27.39	80.29	25	60	0.24	360	627.63
Sanjhara	27.42	79.8	21	60	0.18	226.8	765.44
Katiuli	27.68	79.65	18	60	0.2	216	711.77
Usawan	27.81	79.34	16	60	0.21	201.6	688.21
Rsoola	28.23	79.13	19	60	0.17	1960.8	796.23
Karanpur	28.81	78.6	19	60	0.9	1026	252.13
Agwanpur	29	78	16	60	3.31	3177.6	102.65
Khalilpur	29.62	78.32	8	60	0.18	211.2	765.44
Loha Patti Bhagirnath	28.64	79.15	19	60	1.3	1482	195.63
Haridwar	29.99	78.18	22	60	0.35	264	483.77
Dahyaki	29.73	77.85	12	60	0.12	1044	1012.55
Muzaffarnagar	29.42	77.71	18	60	0.4	226	441.19
Samogara	25.47	82.83	10	60	0.95	570	242.90
Rasoolpur	26.66	81.99	19	60	0.23	262.2	646.34

short-period seismometers (Guralp CMG-6T-1) having a natural period of 1 sec and Kelunji EchoPro digital acquisition system. The microtremor data was recorded at 100 samples per second.The sensor used has the capability of measuring frequency in the range between 1 and 50 Hz, and has the same characteristics in all its three axes. Out of 31 locations, 9 sites were very close to sites of bore-hole drilling that had reached bed rock, i.e. sites with a precisely known thickness of sedimentary cover. Location of microtremor survey locations and drilled borehole sites are shown in Figure 1.

The complete data processing was carried out using Geopsy software. For each station, the time-series of the record was divided into a window of 60 sec duration. Each window was base-line corrected for anomalous trends, tapered with a 5% cosine window, and band-pass filtered. The Fourier amplitude spectra of each selected window were computed and smoothened using Konno and Ohmachi[36] with a smoothing constant value of 40. Then, the average spectral ratio of the horizontal to vertical component (i.e. H/V) in each window was calculated from the equation[16]

$$H/V = \sqrt{(F_{\mathrm{NS}}^2 + F_{\mathrm{EW}}^2)/2F_{\mathrm{V}}^2}.$$

Here, F_{NS}, F_{EW} and F_{V} are the Fourier amplitude spectra in the north–south (NS), east–west (EW) and vertical (V) direction respectively. The average of the H/V spectral ratios obtained for each window is taken as the final H/V ratio of the particular survey location, and the frequency corresponding to the first peak of the H/V spectrum plot is taken as the resonant frequency of the site[12,37].

HVSR values of 31 stations along with its geographical position are presented in Table 1 with the corresponding parameters that help to prove the reliability of the curve obtained in this study. Using uniform window length of 60 sec and anti-trigger algorithm, number of windows ranging from 8 to 27 was obtained. The obtained resonant frequency was greater than 0.12 Hz in all the cases. Standard deviation of resonant frequency fell within the recommended value, indicating the low scattering of frequency values from mean position. Also, the number of cycles was greater than 200 proving that a large number of cycles and windows were used for producing HVSR plots. Every plot thus produced was strictly within the prescribed limit showing good reliability as per SESAME[37] guidelines. Thirty-one H/V spectrum plots are shown in Figure 2. An overall similarity in shape of the resonant frequency curves was observed with most of

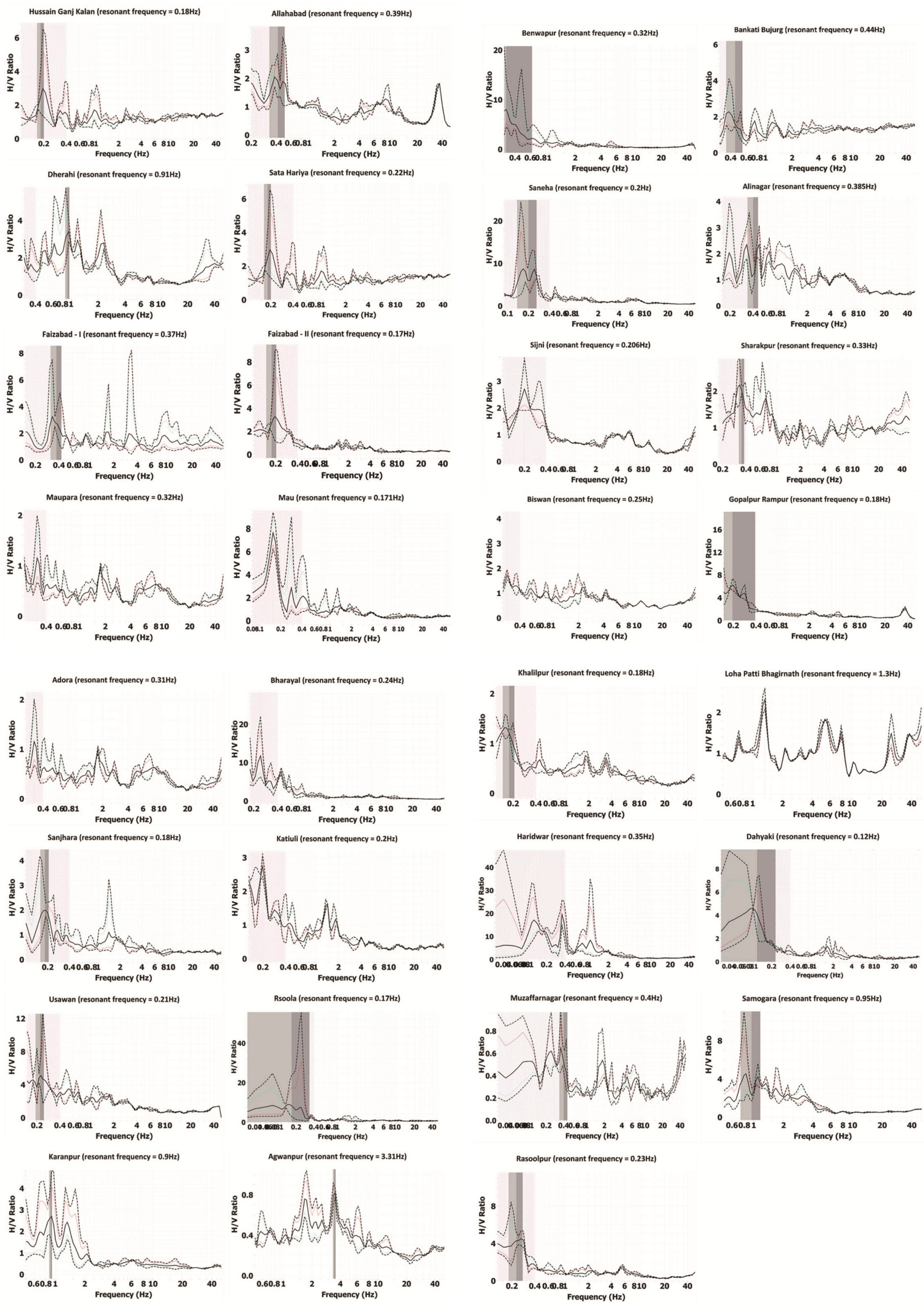

Figure 2. *H*/*V* spectrum plots along with resonant frequency values for all the survey locations carried out in the Indo-Gangetic Plains.

Table 2. Summary of the previously published empirical equations for the estimation of sediment thickness using resonant frequency from microtremor measurements

Author	Empirical relationship	Study area	Comparison	Geology of the area	Sediment thickness covered
Seht and Wohlenberg[14]	$H = 96f_r^{-1.388}$	Western Lower Rhine Embayment in Germany	34 boreholes with data from 102 microtremor measurements	Sedimentary cover with approximate 1000 m thickness	15–1257 m
Delgado *et al.*[16]	$H = 55.64f_r^{-1.268}$	Bajo Segura Basin, Spain	33 microtremor surveys with 23 borehole locations	Sedimentary	3.8–46.1 m
Parolai *et al.*[39]	$H = 108f_r^{-1.551}$	Cologne area, Germany	32 boreholes with 337 data from seismic stations	Sediment thickness varying from 100 to 500 m	10–401.6 m
Hinzen *et al.*[40]	$H = 137f_r^{-1.19}$	Lower Rhine Embayment, Germany	50 microtremor survey points with lithology data	Sedimentary cover with approximate 1000 m thickness	60–1250 m (medium thickness of 600 m)
Birgören *et al.*[41]	$H = 151f_r^{-1.531}$	Istanbul	15 microtremor survey at borehole locations	Sedimentary	20–366 m
Özalaybey *et al.*[42]	$H = 141f_r^{-1.27}$	Izmit Bay area, Turkey	239 microtremor survey with 405 point gravity measurements	Sedimentary cover ranging from thickness of 750 m to 1200m thickness	60–1120 m
Paudyal *et al.*[21]	$H = 146f_r^{-1.2079}$	Kathmandu basin	172 microtremor survey with 2 Boreholes (taken from previous study)	Lacustrine sediments with varying sediment thickness within a few meter	Max.357 m thickness
Biswas *et al.*[42]	$H = 160.9f_r^{-1.459}$	Shillong, Northeast India	70 microtremor surveys with available borehole lithology data	Sedimentary	10–200 m
Del Monaco *et al.*[44]	$H = 129.3f_r^{-1.06}$	Western L'Aquila plain	790 microtremor surveys with available borehole data	Sedimentary layer with 100 m thickness	10–200 m
Khan and Khan[45]	$H = 134f_r^{-1.23}$	Islamabad city, Pakistan	81 microtremor surveys in comparison with already published data	Sediment thickness upto 100 m	4–138 m

them falling in the range 0.17–0.44 Hz. Further analysis of curves showed that HVSR along the edge of the basin showed almost a flat response with small peak at the higher frequency while those inside the basin showed a clear peak response at lower frequency. An increase in resonance frequency was observed in northern part while in southern part of the basin low resonance frequency was observed ranging from 0.18 to 0.33 Hz.

Results and discussion

Comparison of resonance frequency

Srinagesh *et al.*[38] have observed the predominant frequency using source-receiver function for 8 different sites located in central part of Indo-Gangetic basin. All these sites were located on soft alluvial sediments. Out of these 8 stations, 4 of them were far from our survey locations, and hence the remaining 4 sites were used for our comparison purpose. The coordinates of these 4 sites have been marked as numbers 1–4 in Figure 1; the 4 sites are Roorkee – 1, Shahjahanpur – 2, Hardoi – 3 and Sandila – 4. It can also be observed from Figure 1 that the Srinagesh *et al.*[38] locations belong to the central part of the IGP, but the 31 locations of the present study are spread throughout the entire IGP region.

Figure 3 shows the comparison of resonant frequency measured in the present study with Srinagesh *et al.*[38]. It can be observed that the results show good agreement between both the methods. However, the slight difference in values may be attributed to the local geology of the survey locations, and the distance between Srinagesh *et al.*[38] and the present study survey locations. Although both the methods differ in certain fundamental ways regarding assumption of source, path and site effects, they yielded similar prediction of resonant frequency.

Relating resonance frequency with sediment thickness

The inverse proportion relationship that exists between the main resonance frequency of a soil and its thickness is well known in the field of seismic soil response. The inverse relationship is of the form[16]

$$H = a(f_r^{-b}). \quad (1)$$

Several researchers have carried out correlation studies between *H*/*V* spectral ratio peak frequencies and overburden thickness cover, aided by available borehole lithology data. Seht and Wohlenberg[14], Delgado *et al.*[16] and Parolai *et al.*[39] were the first to study the relationship between resonant frequency and the sediment thickness. Other important studies relating to sediment thickness with resonant frequency are in refs 11, 21, 22, 39–45. The empirical equations developed by previous researchers are given in Table 2.

Various authors have developed empirical equations based on 1 : 1 comparison of survey location with available borehole data[14,16,39,41,43–45]. Seht and Wohlenberg[14] have studied both the parameters (i.e. sediment thickness and resonant frequency) and demonstrated that it is possible to establish a direct functional relationship between them despite not knowing the shear wave velocity (V_s).

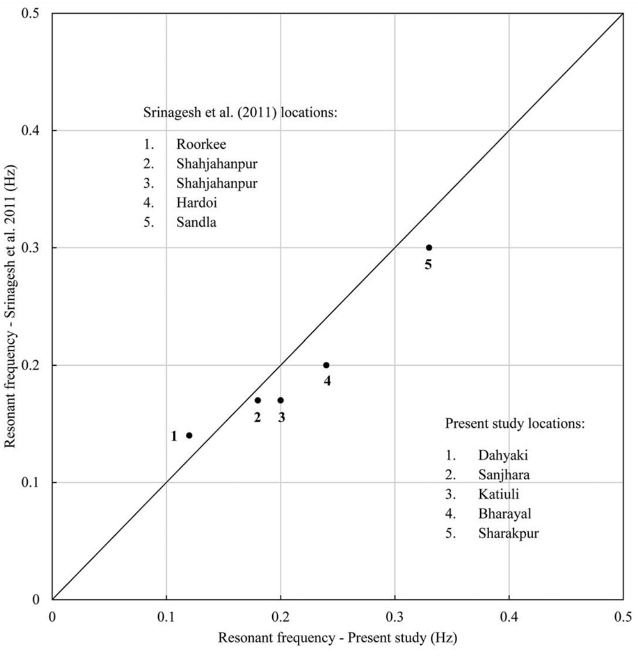

Figure 3. Comparison of resonant frequency from present study with Srinagesh *et al.*[38].

They estimated the value of *a* and *b* and proposed an empirical relationship (eq. (3)) between the fundamental resonant frequency (f_r) and the thickness of soft sediment cover (h) (quaternary sediments), based on 34 boreholes ranging in depth from 15 to 1257 m and data from 102 seismic stations. Hinzen *et al.*[40] established an empirical equation (eq. (4)) based on 50 HVSR measurements with geological profiles from four boreholes which included stratigraphic information from 400 and 1000 m deep boreholes. Özalaybey *et al.*[42] have obtained regression relationship (eq. (5)) based on comparison between 239 microtremor surveys with 405-point gravity measurements. For this, the resonant frequency values were selected using the sites where the HVSR curves showed well-defined spectral peaks with amplitude greater than 3.5 and matching with gravimetric survey. This selection resulted in 47 corresponding resonant frequency values and their sediment thickness values have been derived from the gravimetric bedrock depth map. Out of the previous empirical equations developed for different regions with various soil sediment thicknesses, few authors[14,40,42] have developed equations for sites with deep soil deposits having sedimentary thickness up to 1000 m, while most of them have developed for shallow basin data[11,21,22,39,41,43–45]. Since the IGP has deep sedimentary cover ranging from 0.5 to 4 km (ref. 38), these three equations could possibly be used in estimation of sediment thickness for this region.

Using our observed values of f_r from the peak in the *H*/*V* spectral ratio and the sediment thickness cover data from nine nearby borehole locations, a regression fit of (1) was performed and the following equation was obtained

$$H = 234.45(f_r^{-0.69}). \quad (2)$$

Figure 4 shows the plot of sediment thickness with the resonant frequency, along with the fitted power equation. This equation has a good R^2 value of 0.8865. The equation was obtained by nonlinear regression analysis of the data to fit a power function, by using the curve fitting tool in Matlab. It shows a decreasing trend of sediment thickness with an increase in frequency. This is quite expected as *H*/*V* spectral ratios give rise to peaks at higher frequencies for sites where the bedrock becomes shallower. Further, sediment thickness for all the sites was calculated using the derived equation, and also with the three other applicable relationships developed earlier[14,40,42]. The calculated sediment thickness values have been compared to check the agreement of the present study with previous relationships. The three other applicable relationships are

$$H = 96(f_r^{-1.388}) \text{ (ref. 4)}, \quad (3)$$

$$H = 137(f_r^{-1.19}) \text{ (ref. 40)}, \quad (4)$$

$$H = 141(f_r^{-1.27}) \text{ (ref. 42)}. \quad (5)$$

Figure 5 shows the comparison of residuals between the developed equation and the other three deep soil site equations. It illustrates the variation of error value in the estimation of sediment thickness with frequency. It can be observed that at lower frequencies (0.15–0.3 Hz), the error involved in the estimation of sediment thickness from the three empirical equations is very high, up to 500 m. Equation given by Hinzen *et al.*[40] performs better than the other two equations in predicting the sediment thickness for IGP. It has low magnitude errors in both the low frequency and high frequency ranges. Equation given by Seht and Wohlenberg[14] performs the worst for this particular region. Although the equation follows the general trend as the other two equations, the error associated with it is very high for the entire frequency range. Equation developed by Özalaybey *et al.*[42] gives the highest error for 0.18 Hz, but thereafter it performs the same as the equation given by Hinzen *et al.*[40]. However, the developed empirical equation performs the best, except at 1.3 Hz, among all these equations. Thus, it can be inferred that none of the previously published equations can satisfactorily estimate the sediment thickness of the IGP implying that for accurate estimations of the sediment thickness, the region-specific equation has to be used.

Figure 6 shows the plot of combined equation (eq. (6)) which has been developed by regression analysis by using the data available from the aforementioned deep soil studies and also by including the data from the present study.

$$H = 137.88(f_r^{-1.174}). \quad (6)$$

The sediment thickness and resonant frequency data was digitized[14,40,42]. By combining this data with that of the present study, the combined equation has been developed which has $R^2 = 0.8835$. It is proposed to use the combined equation for estimation of sediment thickness when region-specific equation is not available. This equation has been developed so as to reduce the error in the estimation of sediment thickness which is evident in Figure 6. With the inclusion of the data from the present study to the previously published studies of deep soil sites, it can be observed that the combined equation performs better than the previously published equations; although the

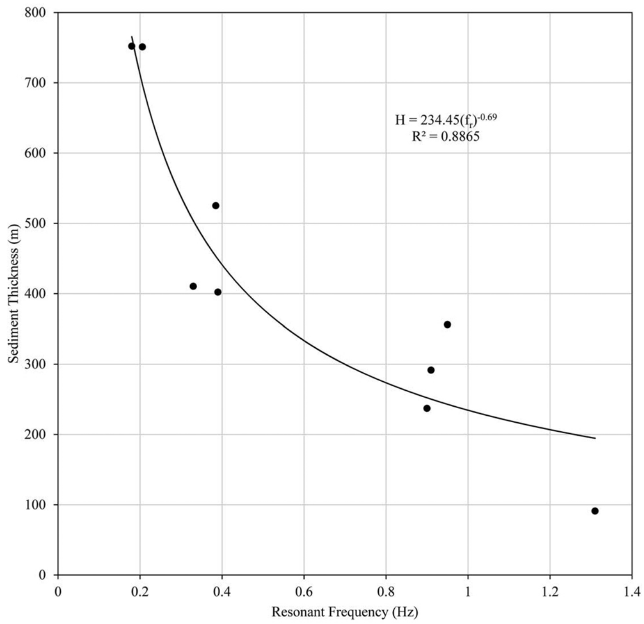

Figure 4. Empirical correlation established between resonant frequency obtained from the present study and the sediment thickness obtained from borelog data.

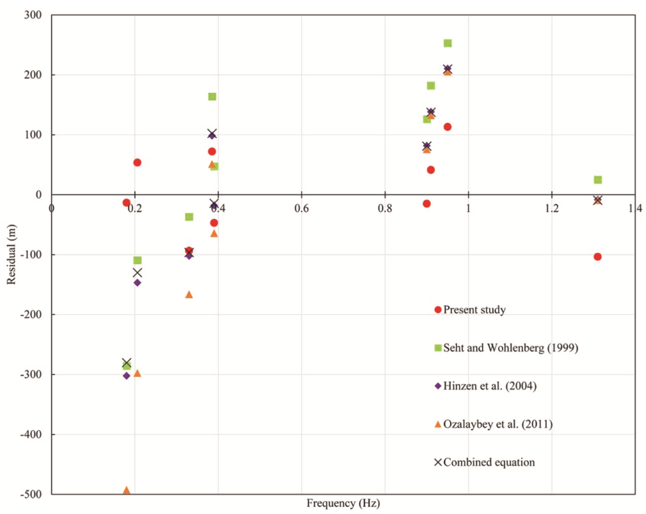

Figure 5. Comparison of residuals in estimation of sediment thickness using previously published equations for deep soft soil sites with the present experimental data.

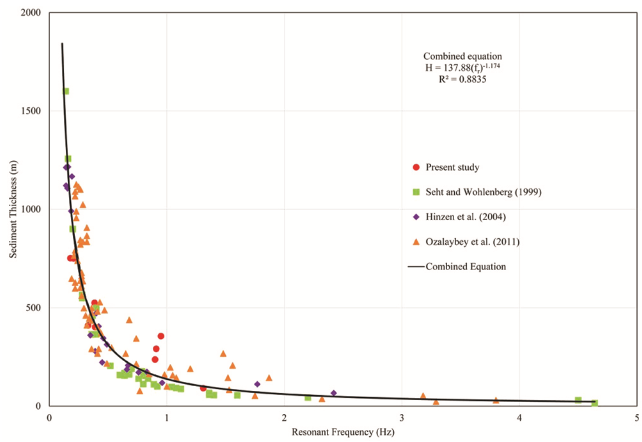

Figure 6. Plot of combined equation developed by using the data from previously published deep soil site studies along with the data from the present study.

data from the present study added to the combined data is only 7%. Hence, based on these observations and results, this combined equation can be used for a preliminary estimation of sediment thickness for any other deep soil site, when no other such correlations are available for that region.

Figure 7 shows the plot of three previously published deep soil site equations, the empirical equation obtained in this study and also the combined equation developed in this study, on a log–log scale. On comparing the equations, it can be observed that the three previously published equations overpredict the sediment thickness for low frequency and underpredict for high frequency. However, the magnitude of under prediction or overprediction is greater by Seht and Wohlenberg[14] equation compared to the other two equations. Özalaybey *et al.*[42] have used sediment thickness obtained from gravimetric bedrock mapping to correlate with resonant frequency. They have not compared the sediment thickness with any bore log, and they have also concluded that the absolute basin depths may vary within ±30% of a given depth value. However, in the present study only reliable bore log data were used for developing the empirical correlation between sediment thickness and resonant frequency. Even though few locations out of the 31 survey locations had low resonant frequency values for example Dahyaki – 0.12 Hz, reliable bore log data were not available for such locations. Perhaps, this may be the reason why the developed equation underpredicts at lower frequency whereas the previously published equations overpredict at the same frequency range, which is clearly evident from Figure 7. Therefore, it has be kept in mind that the equation was developed with sediment thickness data until 750 m depth and using the equation beyond this limit may result in erroneous prediction of sediment thickness. In this regard, future studies can be taken up at particular locations in the IGP where reliable bore logs

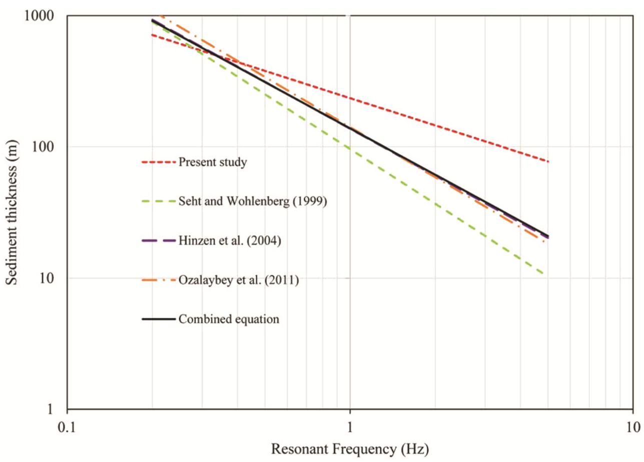

Figure 7. Plot of 4 empirical equations available for estimation of sediment thickness of deep soft soil sites and the combined equation developed after regression analysis.

are available for sediment thickness greater than 750 m, to further improve the applicability of developed empirical correlation in the present study.

Conclusion

The present study is the first attempt to relate sediment thickness of selected sites in the IGP with resonant frequency based on Nakamura technique. Microtremor measurements were carried out in 31 locations of IGP. Out of the 31 locations, 9 surveys were close to boreholes drilled up to bedrock. The following conclusions can be drawn from the study:

(1) The measured resonance frequency varies from 0.12 to 3.31 Hz. An overall similarity in shape of the resonant frequency curves was observed with most of them falling in the range 0.17–0.44 Hz. Further analysis of the curves indicated that the HVSR along the edge of the basin showed almost a flat response with small peak at the higher frequency while those inside the basin showed a clear peak response at lower frequency. An increase in resonance frequency with low amplification was observed towards north direction while in southern basin low resonance frequency with higher amplification was observed.

(2) Comparison of resonance frequency estimated from Nakamura technique with that of source receiver function method for central part of Indo-Gangetic Plain showed good agreement with our present study.

(3) By correlating deep borehole sediment thickness with resonant frequency, an empirical equation was established for IGP, which is: $H = 234.45(f_r^{-0.69})$, having R^2 value of 0.8865. This equation was compared with three other published deep soil site equations. The error in estimation of sediment thickness with these equations was calculated, and based on the poor performance of these equations to predict sediment thickness accurately for the IGP, it was concluded that it would be better to develop region-specific equation for the estimation of sediment thickness for a particular region of interest.

(4) Using the sediment thickness and resonant frequency data from previously published deep soil site studies along with the data from the present study, a combined equation was developed by regression analysis, which is: $H = 137.88(f_r^{-1.174})$ having R^2 value of 0.8835. The proposed combined equation can be used for a quick preliminary assessment of the sediment thickness, when no other such equations are available for a particular region.

However, the applicability of the proposed equation in the present study is limited by the borehole data available for IGP. Future research works can be taken up in this regard to find out the applicability of the present equation for the entire Indo-Gangetic basin. Also, other geophysical methods such as multi-channel analysis of surface waves (MASW) can be performed along with microtremor survey to obtain better estimation of the dynamic properties of subsurface layers of a particular site, since it is also possible to map bedrock using the MASW method, the sediment thickness calculated from both the methods could also be compared.

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