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Research Article

Mapping Sediment Thickness in Shillong City of Northeast India through Empirical Relationship

Rajib Biswas,[1] Saurabh Baruah,[2] and Dipak K. Bora[3]

[1]*Department of Physics, Tezpur University, Tezpur, Assam 784028, India*
[2]*Geoscience Division, CSIR-North East Institute of Science and Technology, Jorhat, Assam 785006, India*
[3]*Diphu Government College, Karbi Anglong, Assam 782462, India*

Correspondence should be addressed to Rajib Biswas; rajivb27@gmail.com

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Modified form of Nakamura method, H/V ratio, is used to assess the site response through estimation of fundamental resonant frequency at 70 sites using three component digital seismographs in Shillong city, capital of Meghalaya in northeast India. With available borehole information, an attempt is made to develop an empirical relationship between sediment thickness and resonant frequency estimated from H/V ratio technique. Simultaneously, shear wave velocities are computed entailing resonant frequency and sediment thickness for these boreholes. We also endeavored building another empirical relation between sediment thickness and V_S. With the help of this, the probable V_S values for other sites were also evaluated. It is observed that shear wave velocities range from 200 to 550 m/s while sediment thickness ranges from 10 to 80 m, implicating the heterogeneity prevailing in the soil layers of the Shillong city.

1. Introduction

It is widely accepted amongst earthquake engineering community that local geology has a dominant role in seismic motion. Soft soils, one of the constituent elements of local geology, are considered as one of the root causes of numerous geotechnical problems because of their low density, high compressibility, and low strength. As a result it becomes potentially collapsible, causing huge settlements of foundations even on low-magnitude loads. This leads to violent shaking resulting in severe damage to buildings sited over them. Moreover, damage caused by occurrence of earthquake depends not only on its magnitude and epicentral distance, but also on local site effects which are essentially frequency dependent. They are caused by topography, sediment thickness, soil conditions, and geology of the area. For seismic hazard assessment, the site effect is typically represented by resonance frequency and the associated ground motion amplification. Several methods exist, such as array data analysis, Nakamura method of horizontal to vertical H/V spectral ratio of ambient noise, site to reference spectral ratio, and receiver function type analysis. Out of these, Nakamura method, that is, use of ambient noise records for determination of fundamental resonant frequency, has recently gained worldwide acceptance because of quick data acquisition. The amount of amplification depends on several factors including layer thickness, degree of compaction, and age [1]. One of the many reasons for choosing ambient noise by several authors is that it allows the quick and reliable estimate of site characteristics of any type of an area. There are many instances of successful utilization of the H/V spectral ratio estimate towards studying fundamental frequency from ambient microtremors in urban environments ([2–8] and many others). The proximity of fundamental frequency of a site to the existing man-made structures causes damage of the later owing to resonance effects. Therefore, investigation of each site condition is an important step towards earthquake hazard mitigation.

Drilling boreholes allows investigators to obtain detailed information, but they are treated as time consuming as well as very expensive process. It is however affirmed that horizontal to vertical ratio in the case of large impedance contrast between overburden thickness and bedrock provides a good estimate of the fundamental frequency of soft soils but not of higher harmonics. Recently, different studies showed that noise measurements can be used to access the overburden thickness. Apart from this, shear wave velocity which is a very crucial parameter in hazard estimation also bears a functional relationship between overburden thicknesses and frequency of resonance, as established by Delgado et al. [9, 10]. In order to experimentally determine this crucial parameter, adoption of geophysical techniques becomes one of the suitable options. Nonetheless, consumption of enormous time and money during this process stands as a great hindrance for such kind of undertakings. However, from known values of resonant frequencies and thicknesses, it is customary to build up power law relating sedimentary thickness and shear wave velocity. Thus, adopting empirical relationships allows one to quickly have an overall view of the entire area. The empirical relationship enables one to delineate the zones of vulnerability. Even the inaccessible region in the context of information of overburden thickness as well as other related parameters could be fruitfully accessed by these kinds of built-in relationships. Simultaneously, for hilly terrain like Shillong, this could pave the way for detailed study.

The aim of this paper is to display these methods to determine the distribution and the thickness in Shillong region, an area where these types of soils are known to exist but where the available geotechnical information is insufficient for such determinations of shear wave velocity. Simultaneously, derivation of empirical relationships between the main resonance frequencies, overburden thickness obtained by using two H/V spectral ratios, and shear wave velocity in the Shillong area remained also as one of the prime objectives.

2. Geological Settings and Seismicity

Shillong city, capital of Meghalaya, India, is situated in the almost elliptically shaped Shillong Plateau (SP). It covers an area of 6430 square kilometer, with an average elevation of 1000 m and approximate population of 150000. The SP with an Archaean gneissic basement and late Cretaceous-Tertiary sediments along its southern margin is bounded by the Brahmaputra River to the north and by the Dauki fault to the south [12, 13].

The study area is marked by Shillong series of parametamorphites, which include mostly quartzites and sandstones, followed by schist, phyllites, slates, and so forth. Prominently, a conglomerate bed containing cobbles and boulders of earlier rocks, that is, Archaean crystalline, remains as main constituent of the Shillong series, which formed the basement over which the Shillong series of rocks were originally laid down as sedimentary deposits in Precambrian, probably in shallow marine conditions [14, 15]. The Shillong groups of rocks are intruded by epidiorite rocks, known as Khasi Greenstone as outlined in Figure 2. The Khasi Greenstone is a group of basic intrusives in the form of linear to curvilinear shapes occurring as concordant and discordant bodies within the Shillong group of rocks and had suffered metamorphism [16]. These rocks are widely weathered and the degree of weathering is found to be more in the topographic depressions than in other areas. The metabasic rocks are more prone to weathering than the quartzite rocks. Additionally, valley fill sediments filled the low lying areas. Numerous lineaments trend in NE-SW, N-S, and E-W directions in the area [17].

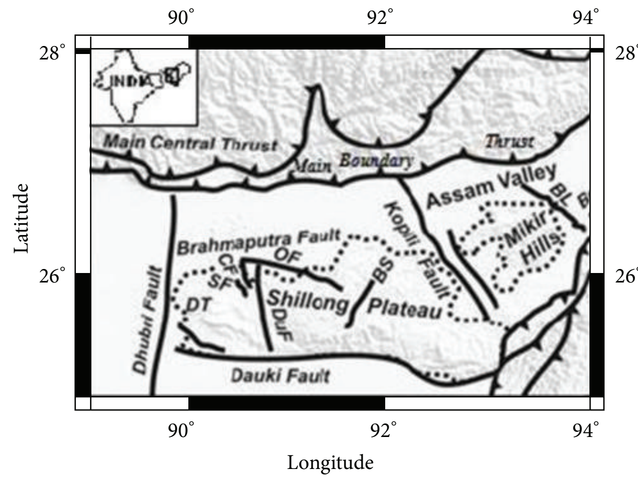


Figure 1: Tectonic map showing the major features around Shillong Plateau (as modified after Baruah and Hazarika, [11]). The inset map shows the study region. BS: Barapani shear zone, SF: Samin fault, DT: Dapsi thrust, DuF: Dudhnoi fault, OF: Oldham fault, CF: Chedrang fault, and BL: Bomdila lineament.

The SP within which our study area falls is regarded as one of the most seismically active regions in India. The Plateau is separated out from the peninsular shield and moved to the east by about 300 km along the Dauki fault [18]. The area is surrounded by active faults such as Dhubri fault to the west, Oldham fault to the north, Dapsi thrust to the south, and the Kopili fault to the northeast [13] (Figure 1). As portrayed in Figure 1, some prominent faults are Chedrang fault, Dudhnoi fault, and the Barapani lineament/shear zone. Northern end of the SP was the source area for the 1897 great Shillong earthquake Ms 8.7 that caused severe damage and more than 1500 casualties [19]. Another significant earthquake of June 1, 1969, with a magnitude 5.0 and epicentral distance of 20 km from Shillong [20] was also strongly felt. As reported by Gupta and Singh [20], there has been a gradual decrease in P-wave velocity yielding a speculation that the region is experiencing a dilatancy stress precursory to a large earthquake (Semnov, 1969). According to Khattri et al. 1992 [21], the Shillong Massif shows a pertinent seismic activity with an average of 10–15 small magnitude earthquakes per day. Over the past hundred years, there were instrumental records of 20 large earthquakes [22]. During the recent past, there has been a noticeable rise in the number of felt earthquakes whose epicenters lie within the vicinity of Shillong city. One event ($M > 5$) occurred on August, 2009, [23] that generated significant ground acceleration. Besides, the September, 2011, earthquake ($M > 6$) caused heavy causalities in northern India whose strong tremors were felt in this study region. It is worthy to mention that damage associated with the occurrence of earth tremors has been found not only due to magnitude of the earthquake of earth tremors and its epicentral distance, but also due to local site effects which

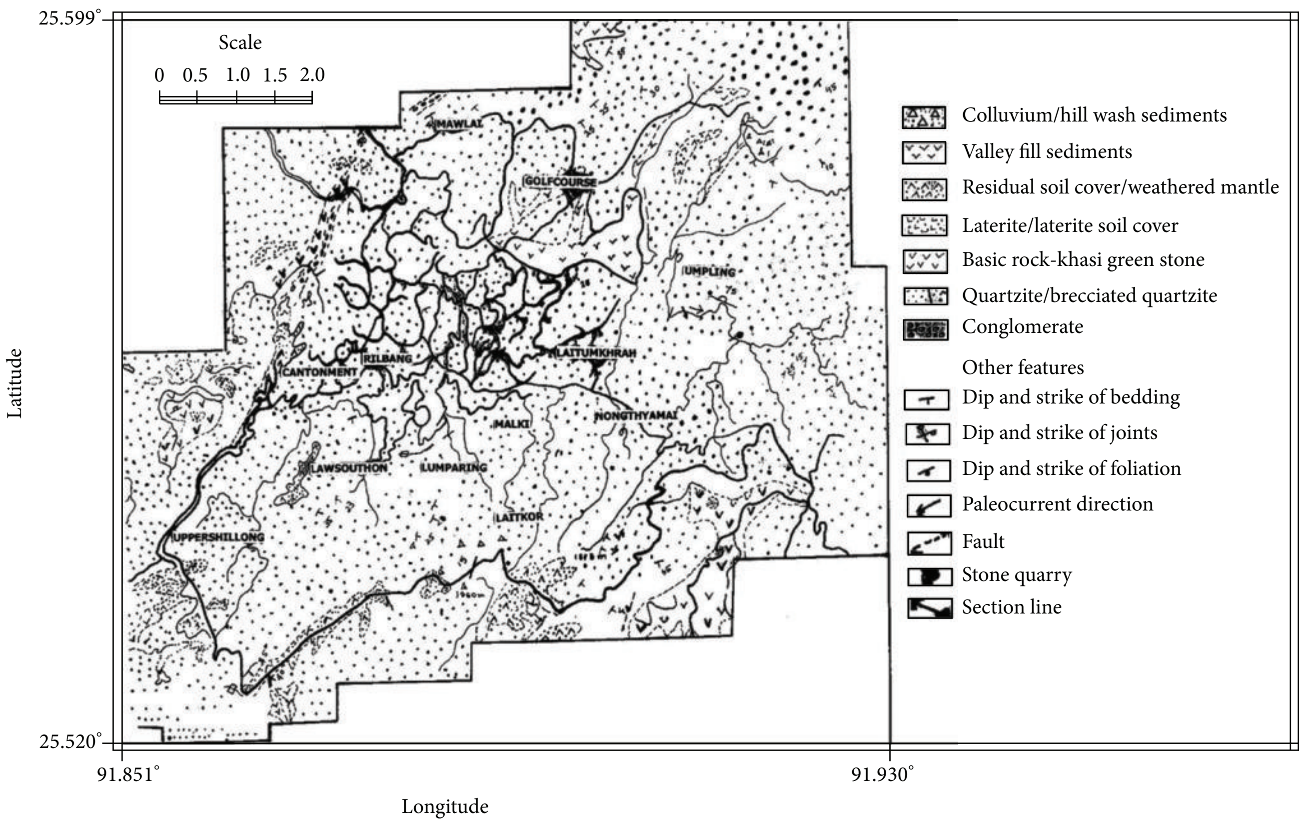


Figure 2: Geological map of Shillong city. Geological map of greater Shillong area, east khasi hills district, Meghalaya.

are essentially frequency dependent caused by the topography and geology of the site.

With installation of adequate digital seismic networks set up by NEIST-J (North East Institute of Science & Technology, Jorhat), National Geophysical Research Institute (NGRI), and India Meteorological Department (IMD), there has been a remarkable improvement in recording and locating the lower magnitude earthquakes [13]. During the past few months, there have been a few felt earthquakes in Shillong city that occurred within 100–150 km radius. This populous city of Shillong is not far from the source zone of the great earthquake of 1897 (M_S 8.7). Intense seismicity beneath the Plateau is conjectured to be caused by pop-up tectonics of the Plateau between Dapsi thrust and Oldham/Brahmaputra fault [13]. Further, to the far east of SP, Kopili fault is active that caused two recent felt earthquakes (Mw 5.1 and 6.2) in August and September, 2009, respectively [23]. Considering this recent rise of felt tremors and its surrounding active tectonic settings, there is a need to systematically investigate the overburden thickness pertinent to Shillong city which is regarded as the root cause for severe damage as observed by Cara et al., 2008, and many others [24].

3. Data

Around 70 sites in Shillong city area were covered during the ambient noise survey (Figure 3). In the survey, we utilized three-component Teledyne Geotech velocity sensor with sensitivity factor of 1s, being equipped with 24 bit Reftek Digitizer and recorder. The data was sampled at 100 samples per second. A continuous recording of eight hours especially during night hours was done for data acquisition. While processing data, utmost care was taken to obliterate the transients of anthropic origin. More emphasis was laid on stationary portion of ambient record. Instrumentation and data processing had been detailed in Biswas and Baruah, 2011 [25]. Out of these seventy sites, ten sites were in the immediate neighborhood of borehole drillings.

4. H/V Results

In conformity with the guidelines of SESAME [26], the H/V spectral ratios were evaluated for 70 sites. The H/V ratio estimates yielded two categories of sites showing fundamental frequencies, namely, lower and higher. The lower category of fundamental frequency ranged between 1 and 3 Hz. The other sites exhibiting fundamental frequencies above 3 Hz were classified as higher category. For example, the lower category of frequency is displayed in Figure 4(a), having fundamental frequency of 2.2 Hz, whereas Figure 4(b) represents the higher category of frequency which is above 3 Hz.

Generally, there exists a notable contrast in the mechanical properties of the soft soils and hard rock. H/V spectral ratio method is rooted on the theme that there exists a soil of low rigidity overlying a layer of more rigidity. Consequently, for hard rock sites, the ratio emerges to be flat. Apart from this, stiff soils and soft rocks exhibit different properties differing slightly in mechanical characteristics. Nevertheless,

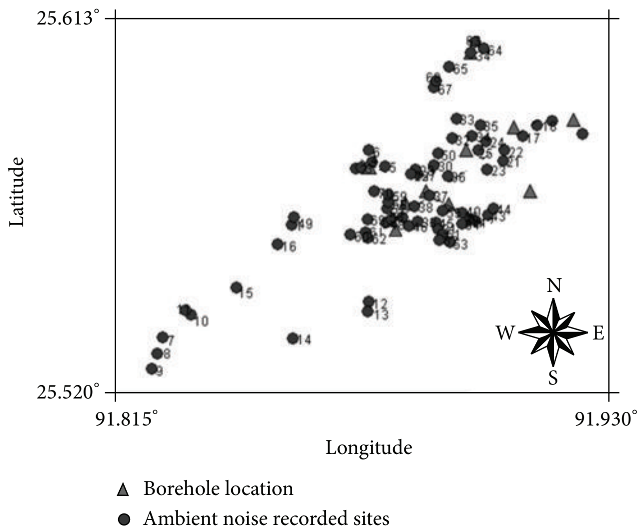


Figure 3: Location of ambient noise recording sites (filled circle) along with borehole locations (filled triangles).

the spectral ratios resulting from soft soils could easily be distinguished from the ones derived in case of stiff soils or soft rock. The point of distinction arises in terms of larger amplitude in lower frequency in the former case relative to the later. However, it is observed to be slight difference in the frequency of resonance as computed from the peak of spectral ratio. The trend towards observation of higher frequency of resonance could be related to thinner layer, supplemented by shallower base formation.

Spatial interpolation of frequency of resonance as determined from spectral ratios led us to the contour plot (Figure 6(a)). It is clear that some sites in certain pocket areas show peak values at higher frequencies of 5 to 7 Hz. Some sites in the centre of the city, on the other hand, exhibit lower fundamental frequency in the range of 1 to 2 Hz. It appears that these sites are marked by the presence of weathered soil cover, as evidenced in the geological map. Of particular significance is that the possibility of having overburden thickness beneath the sites cannot be also ruled out. Several researchers around the world have observed this type variation of resonant frequencies in their region where they mostly attribute the lower resonant frequencies to the existence of higher overburden thickness. Meanwhile, in our observations we also come across sites having higher range of frequencies. This might be caused by the harder soil strata beneath the surface. Additionally, thinning of sediment cover can also be a contributing factor for the observation of higher frequencies. In the next section, we seek to investigate the correlation of resonant frequencies with the sediment cover thickness as evidenced by the available borehole information.

5. Relating Resonant Frequency with Thickness

Several researchers carried out correlation studies between H/V spectral ratio peak frequencies and overburden thickness cover, aided by available borehole lithologic data. To name a few, Seht and Wohlenberg [27], Delgado (2001), and Parolai et al. [28] were the pioneers. Seht and Wohlenberg [27] showed that the frequency of resonance (f_R) of a soil layer is closely related to its thickness (h) through the relationship

$$h = af_R^{-b}. \tag{1}$$

Using our estimates of the f_R (from the peak in the H/V spectral ratio) and overburden thickness from the borehole data, a linear regression fit of (1) was performed and it yielded the following equation:

$$h = 160.94 f_R^{-1.459}. \tag{2}$$

Values of a and b of the correlations have been provided in Table 1.

Table 1: Estimated parameters in (2).

a	b	Δa	Δb
2.2067	1.4591	0.1582	0.2474

Figure 5 shows a comparison between our equation and the relations obtained by other researchers such as Parolai et al., 2002, and Seht and Wohlenberg, 1999. Consider

$$h = 108 f_R^{-1.551}\ [28] \tag{3}$$

$$h = 96 f_R^{-1.388}\ [27]. \tag{4}$$

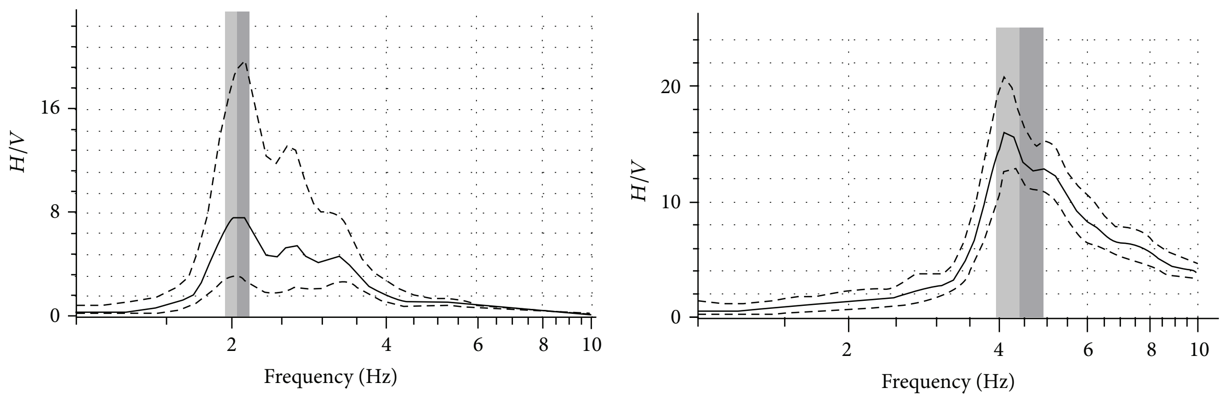
Equation (3) is derived on the basis of the data available up to depth less than 402 m; similarly, equation (4) was based on borehole information as deep as 1219 m. Comparatively, in our study borehole depth was calibrated up to a depth of 205 m.

Figure 5 illustrates the variation of thickness with frequency. All (2), (3), and (4) exhibit estimates of overburden thickness which are found to be declining with rise 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. Of significance is that most of thickness emerging out from (4) is quite scattered. However, considerable match between estimates of thickness by (2) and (4) could be observed. Noteworthy is the fact that the calibrated depth in our study was relatively small compared to Seht and Woohlenberg, 1999. Despite this, we contemplated good convergence in the entire frequency range. Notwithstanding, large divergence was divulged by estimates of (3). All three equations yielded similar estimates of sediment thickness in the frequency range of 1.5–3 Hz. Towards higher frequencies, the depth became shallower. Considering all these, the newly derived relationship was quite at par with the other two established and widely accepted empirical relationships.

6. Average Shear Wave Velocity (V_S) Thickness Relationship

Delgado et al. [9, 10] first highlighted the relationship between the sedimentary thickness and the average shear wave velocity of soft sedimentary column. They derived a power of the following form:

$$\overline{V_S} = ch^d. \tag{5}$$



(a) Site number 21 (b) Site number 30

FIGURE 4: (a) Lower resonance frequency estimates. (b) Higher resonance frequency estimates. The bold vertical line represents the highest amplitude corresponding to the resonant frequency. The dashed lines indicate the deviation in H/V ratio whereas the solid line points to the average estimate.

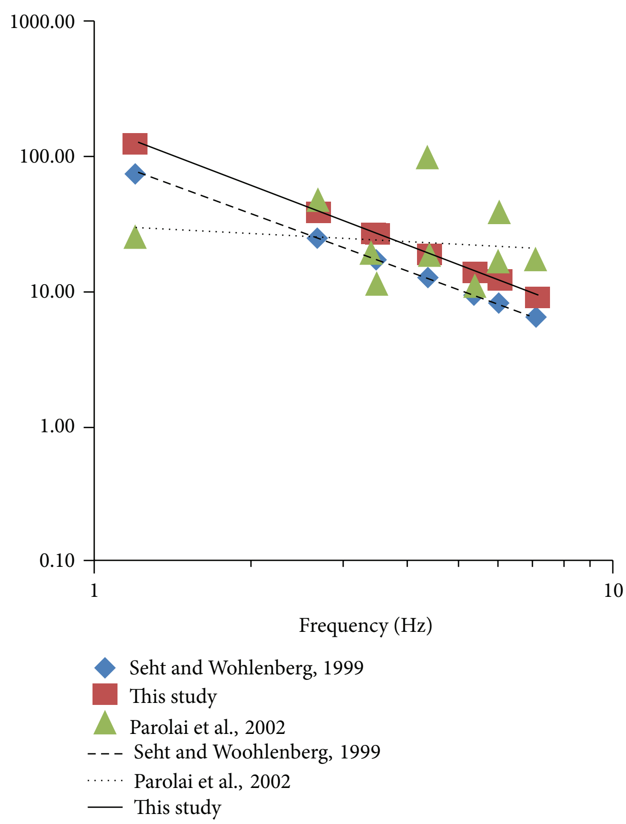


FIGURE 5: Fundamental resonant frequencies calculated from H/V spectral ratios versus sediment thickness from borehole data. The solid line is fit to the data points according to (2) whereas the dashed and dotted lines correspond to relations (3) and (4).

In addition to this, there is another well-known relationship adopted by many researchers [28, 29]:

$$f_R = \frac{\overline{V_S}}{4h}. \tag{6}$$

Using the h values estimated from (5) and the fundamental f_R estimated for sites where borehole information was available, the average shear wave velocity and h data were fitted to (4) which generates the following equation. While attaining this power law ($V_s - h$), we took utmost care in choosing the best control points accrued from borehole and geotechnical data in Shilling region. Consider

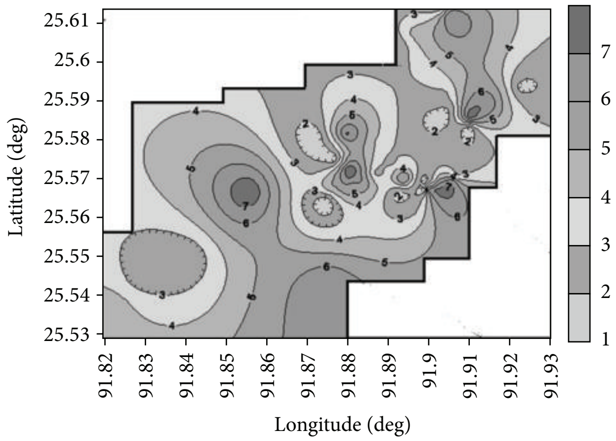
$$\overline{V_S} = 59.415h^{0.596}. \tag{7}$$

Taking into account (2) and (7), it seems that the minimum impedance contrast between sedimentary layer and the bedrock, estimated from velocity contrast alone, is slightly less than 3 encompassing the whole frequency range that we analyzed. It is to be noted that, as reported by Bard, 1999 [30], the implied impedance contrast (≈3) is quite comparable to the impedance contrast (>3) emerging from the density difference between sedimentary cover and underlying bedrock formation which is adequate to give rise to big conspicuous H/V spectral ratio peaks.

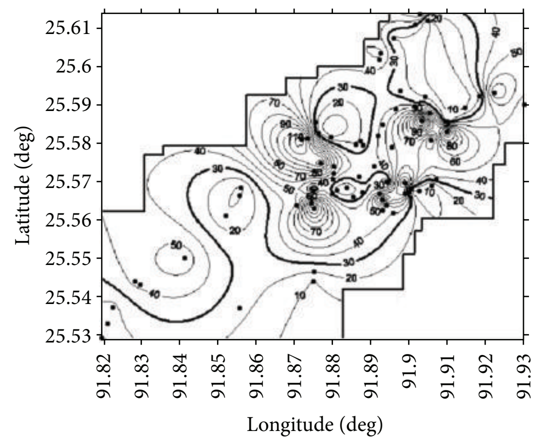
In earthquake engineering, the average shear wave velocity in the uppermost 30 m plays a very vital role. Considering that, we discuss our findings for implementing them as soil classification scheme in Shillong area. However, this classification is constrained by two facts. First, it associates only 1D effect. Presence of 2D or 3D effect nullifies this classification [29]. Secondly, we cannot ignore the plausibility of amplification of ground motion pertaining to sites, marked by sedimentary thickness thinner than 30 m at high frequencies.

As per NEHRP classification, consistent with those made by Ambraseys et al. [31] and Boore et al. [32], the corresponding classification for Shillong area is depicted in Figure 7. It is evident that the shear wave velocity increases with depth or in other words as with increase in overburden thickness. The subsoil classification is based on average estimates of shear wave velocity over the upper 30 m of the site. The site geology has been defined as rock, >750 m/s, stiff soil, 360–750 m/s, soft-soil 180–360 m/s, and very soft soil <180 m/s. With this classification, shear wave velocity less than 200 m/s pertaining to very soft soil could be observed in one of the control points, as illustrated in Figure 7.

It follows that the average shear wave velocity in the uppermost 30 m could be well estimated by adopting (7) for



(a)



(b)

FIGURE 6: (a) Contour showing the distribution of fundamental frequencies from HVSR. (b) Contour showing distribution of overburden thickness in Shillong area.

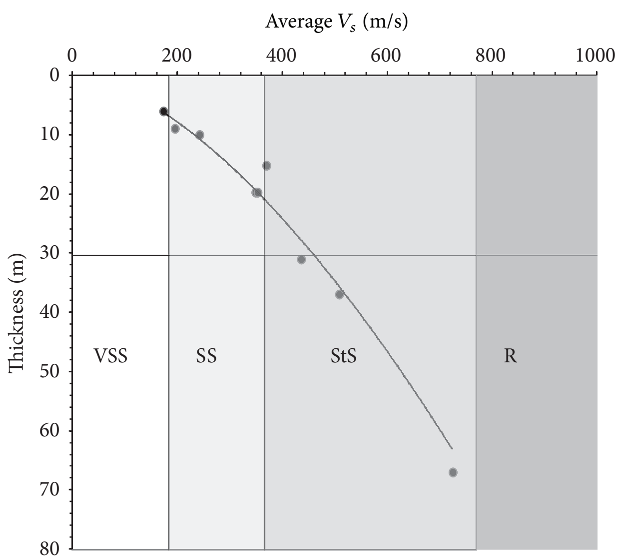


FIGURE 7: Average shear wave velocity versus sediment thickness h. Dots indicate the V_s values calculated by means of (4). VSS: very soft soil; SS: soft soil; StS: stiff soil; R: rock. The line drawn horizontally represents the sediment thickness corresponding to the average V_{S30}.

those sites with overburden thickness of 30 m. As the number of control points is very small, hence getting a proper risk-relevant classification of such sites requires more detailed investigation with precise measurements of both sediment thickness and bedrock velocity.

Using the frequency of resonance in Shillong region as accomplished in [25] the soil thickness was calculated for the whole area by (2). Figure 6(b) displays the respective map. Small inconsistencies between overburden thicknesses measured at borehole drillings and the computed ones shown in Figure 7 may be attributed to the interpolation procedure used for yielding a continuous map. The location of the ambient noise survey was superposed and the investigated area has been split into zones with thicknesses >30 m and <30 m, respectively. Noteworthy is the fact that overburden thickness is well constrained only in areas with dense, neighboring points.

7. Conclusion

The region contains a significant portion of valley fill sediments. From available geotechnical information, it was known that some of these accumulations were soft soils, but their exact distribution and thickness in most of the region were unknown. The H/V spectral ratios of microtremors were used to compute the distribution of these soils as well as their thickness. Based on this, we endeavored to establish quantitative relationship between frequency of resonance of soil and its thickness (h-f relationship).

The results obtained have demonstrated the presence of soft soils throughout the area under study, although their thickness varies irregularly. The substantial thickness estimated for these soils imply poor geotechnical characteristics for the whole recent overburden thickness.

The interpolation of these results has permitted us to prepare a map which reflects the spatial distribution of soft soils in the entire zone including their frequency of resonance and thickness. These maps are of great interest as an initial document for the soil in this area, as well as for the preliminary estimation for the foundation depth of public works. Additionally, it is essential for seismic zoning because it implicates the boundaries of materials more susceptible to amplification of soil movements during an earthquake, because it offers information on both static and dynamic characteristics, namely, the thickness and frequency of resonance, respectively.

These results demonstrate the utility of the method of the H/V spectral ratios of microtremors in the investigation of soft soils. Its subsequent use together with frequency of resonance obtained from the H/V spectral ratios of microtremors allows the thickness of soft soils to be quickly and reliably determined. The H/V spectral ratio of seismic noise was computed for the sites which were in close neighborhood of boreholes where the thickness of the sedimentary cover was known. Consistent with previous studies, a relationship between sediment thickness and the frequency of the main peak in the H/V spectral ratios was calculated. The newly derived relationship, validated for the area of Shillong city, yields better estimates of sedimentary cover thicknesses.

Subsequently, we estimated the shear wave velocity distribution with depth within the sedimentary column and the average shear wave velocity, V_S, depending on the thickness of the column. This enabled us to do a classification of the sedimentary cover, which can be used for seismic hazard assessment. Moreover, optimal response spectrum can be accomplished entailing thicknesses less than 30 m.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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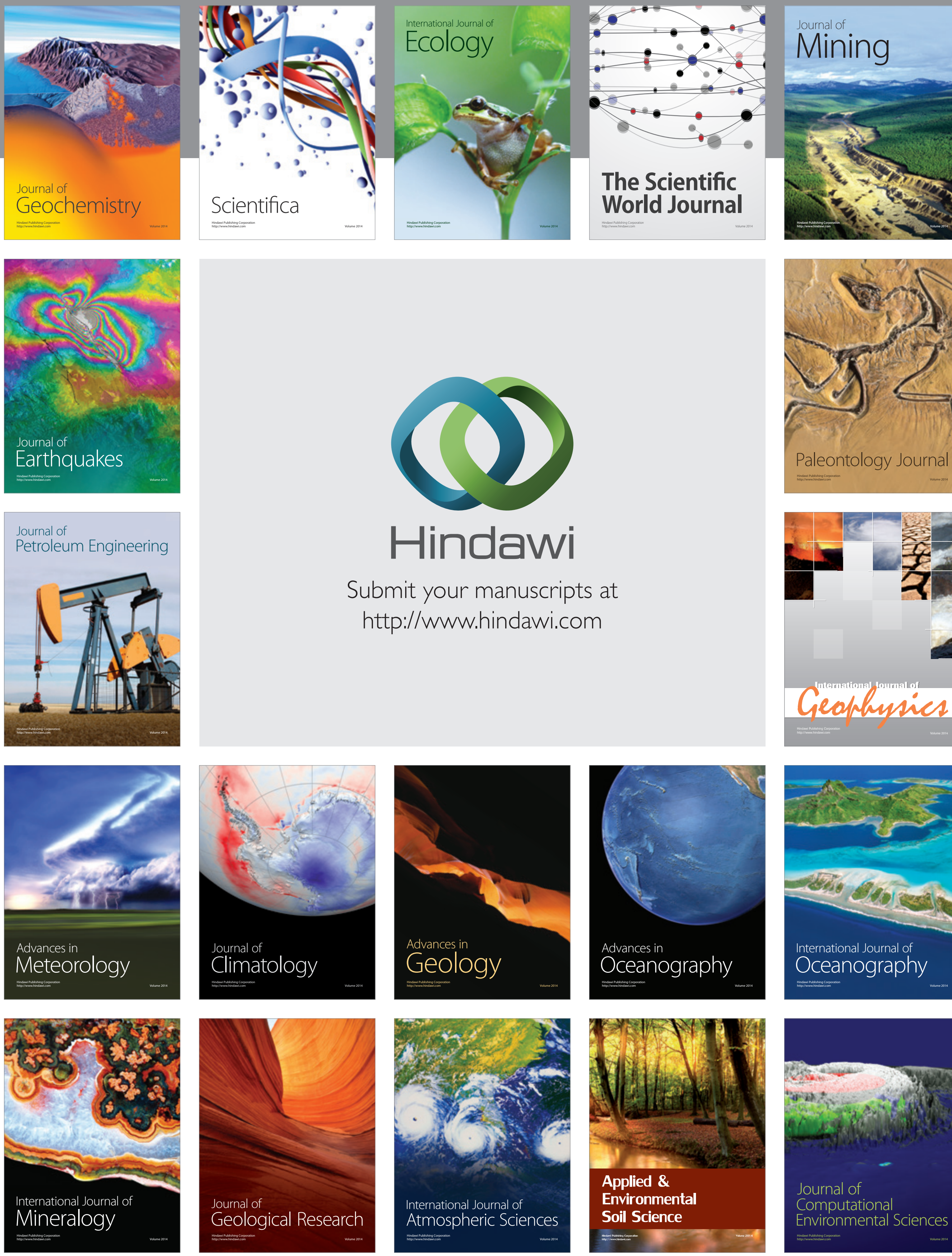
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