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# Site Effects Estimation Using the Horizontal to Vertical Spectral Ratio for Different Geological Formations

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**Abstract**
The University of Lagos (UNILAG), Lagos, Nigeria, and Bukit Ledang, Malaysia, are witnessing rapid development in terms of the construction of new buildings. Geologically, while Lagos is a coastal zone characterized by sedimentary rocks, Bukit Ledang has a hilly topography with rocks from the Paleozoic to Quaternary ages. In this study, we present the ambient noise recordings obtained from locations in each study area and analyze them using the Nakamura technique of horizontal to vertical spectral ratio (HVSR) to determine the predominant fundamental frequency. The result indicates that the fundamental frequency for Bukit Ledang ranges from 2.32 to 2.56 Hz, while that for UNILAG ranges from 0.85 to 1.29 Hz. The peak amplitude for Bukit Ledang (>2) is higher than that of UNILAG (< 1.5), an indication that the impedance contrast between the overlying layers and seismic bedrock is greater at Bukit Ledang, suggesting a possibility for higher amplification. The depth to the stiff layer estimated for Bukit Ledang is about 20 m, while that of UNILAG is about 30. These estimates correlate well with borehole logs from both areas. This study has shown that the characteristics of the HVSR curve are a function of the geology and, as such, can be utilized to provide good and reliable information about site effect parameters such as the fundamental site frequency. Also, with this technique, design criteria can be defined for new buildings to reduce the probability of soil-structure resonance that can result in collapse in the event of ground motion. Furthermore, this technique is well suited for urban areas and can be readily deployed for microzonation studies and other applications.

***Keywords***: *Horizontal to Vertical Spectral Ratio, Site effects, Impedance Contrast, Amplification, Lagos, Ledang.*

## Introduction

Ground motion such as seismic events, machine vibrationn etc., can pose a significant threat to the stability of structures and induce other forms of hazards such as liquefaction and landslides. Studies of past seismic events have shown that the local geological characteristics, i.e. the soil condition at the site, play a significant role in modifying ground motion in terms of its amplitude, frequency content and duration (Lacave *et al.*, 2014, Fan *et al.*, 2019). These characteristics are termed site effects, which tend to amplify or attenuate the input ground motion.

Site effects studies are essential for estimating the level of damage caused by earthquakes, constituting a basic stage in earthquake engineering studies, which is important when designing structures and it involves the estimation of the site's amplification and fundamental frequency. In determining the site amplification (stratigraphical), the knowledge of the shear wave velocity (Vs) of the subsurface - an indication of the stiffness of the soil is a key parameter. On the other hand, the fundamental frequency, $f_0$(natural frequency) provides insights about the frequency at which such amplification would occur.

Several techniques can be used to study site effects, which can be broadly classified into numerical simulation and statistical empirical relation methods (Li *et al.*, 2022). The latter is based on the acquisition of strong motion and microtremor measurement, of which the Horizontal to Vertical Spectral Ratio (HVSR) can be adopted. The HVSR provides a simple and straight forward means of estimating the site's fundamental frequency, a key site effect parameter. Developed in 1983 by Japanese researcher Yuta Nakamura, the HVSR method has been identified as an effective, inexpensive, and environment-friendly geophysical method which can be applied in various areas, including populated and residential areas (Haeurudin et al, 2020).

The HVSR method is a technique that utilizes microtremors generated by man-made activities for estimating the resonance frequency and amplification of ground motions influenced by a surface layer (Abou-Jaoude et al, 2020), this is done by calculating the ratio of the horizontal component to the vertical components of microtremors and earthquake motions (Nakamura, 2019) from which two key subsurface parameters for site effect can be obtained – site's fundamental frequency and amplification. The amplification obtained is however subject to debate as there is still no consensus that the obtained amplification is related to

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the soil amplification in most cases due to the large errors observed (Rong *et al.*, 2016). Apart from the site's fundamental frequency, parameters such as the overburden thickness (Alonso-Pandavenes *et al.*, 2022, Sharma *et al.*, 2024) and vulnerability index (Prasetya *et al.*, 2024; Ismail *et al.*, 2024) indicating high hazard-risk locations can also be estimated.

The fundamental frequencies of buildings of different heights can also be estimated using the HVSR method by taking microtremor readings at the top, middle and base of a building (Stanko *et al.*, 2017). Thus, with the use of the HVSR method, an understanding of the soil – structure resonance can be inferred. Hence, an idea of the site's fundamental frequency can be used as input to provide guidelines for the design and building of structures to mitigate against the adverse effects of ground motion (building collapse, landslide etc.).

This study presents the result of HVSR measurements conducted at two different locations: at the University of Lagos, Nigeria and at Bukit Ledang, Malaysia with the aim to determine the fundamental frequency and depth to seismic bedrock at both locations.

**Study Location**

The study presents the results of HVSR measurements conducted at different geological environment – University of Lagos, Lagos Nigeria and Bukit Ledang, in Malaysia, both having different geology (Figure 1.0). Ledang is located in the Tangkak district of the Malaysian peninsula at approximately LAT 2°16'6.41" N and LON 102°32'19.36" E and is characterized by the prominent Mount Ledang (or Gunung Ledang) which is the highest peak in the region. It has a generally hilly topography, forming part of a massif that spans 8,611.9 hectares which is covered by tropical rain forest that serves as a critical water catchment area for the states Johor and Melaka. The geological distribution of the Ledang area is characterized by rocks from the Paleozoic to Quaternary age. The Triassic Gemas formation is widespread in the area consisting of interbedded tuffaceous sandstone and shale. The Gemas formation is unconformably overlaid by the Cretaceous Ma'Okil formation which are interbedded argillite and arsenic units, rudite and volcanic rocks (Meng et al, 2017). Bukit Ledang is relatively sparsely populated compared to the main city, it is a high-brow residential area experiencing rapid developments of both commercial and residential buildings.

Lagos, however, is located at the University of Lagos at approximately LAT 6°30'40" N and LON 3°24'52" E in the western Nigeria coastal zone, a zone of coastal creeks and lagoons (Pugh, 2004) developed by barrier beaches associated with sand deposition (Hill & Webb, 1958). It has a generally low-lying topography laying in marshland of vast mangrove and freshwater and mangrove swamps surrounding a small and much-deserted tableland consisting of freshwater swamp, mangrove swamp, sandy plain vegetation, and rainforest (Lewis, 1997). Lagos and its surrounding area are located within the Dahomey sedimentary basin and are characterised by two bands of sand separated by silty mud (Ayolabi et al, 2013). The surface geology is made up of the Benin formation (Miocene to Recent) and the recent littoral alluvial deposits. The Benin Formation consists of thick bodies of yellowish (ferruginous) and white sands (Jones and Hockey, 1964). It is friable, and poorly sorted with intercalation of shale, clay lenses and sandy clay with lignite. The formation is overlain in many places by a considerable thickness of red earth composed of iron-stained regolith formed by weathering and ferruginization of the rode (Onyeagocha, 1980). The University of Lagos is a densely populated area with small, medium and large structures constructed at different locations, these structures include hostels, lecture theatres, offices etc housing over 50,000 students and staff in the university.

**Methodology**

The HVSR is a passive seismic technique that uses ambient seismic noise, which is present everywhere in nature to determine the resonance characteristics of a site. The microtremor signals are measured using a three component sensor coupled to the ground and a seismometer. Using the standard Fourier Transform analysis, the power spectrum of the three components are obtained and subsequently, the ratio of the horizontal to vertical spectra is estimated (Kawase *et al.*,2018; Molnar *et al.*, 2022). The result of this analysis is the HVSR curve, from which resonance frequencies, associated with amplitude peaks can be observed on the curve. The frequency of the first peak is associated with the site's fundamental frequency ($f_0$).

For this study, HVSR measurements from two countries with different geology – Bukit Ledang, Malaysia and University of Lagos (UNILAG) Campus, Lagos Nigeria. For each site, HVSR measurements were conducted at four locations (Figure 1.0 and 2.0). Measurements were taken at Bukit Ledng, Malaysia (locations 1 – 4), using the PASI gea24 seismograph and a three component geophone with frequency of 2Hz.

The duration of the microtremor record was 30 minutes at each location.

In the case of UNILAG (locations 5 – 8), data acquisition was done using the ABEM Terraloc Mk6, alongside a 3-componet geophone with frequency of 4.5Hz. Each component of the geophone was connected to different take outs of the seismic cable. To achieve a data record suitable for HVSR processing, several records consisting of 32 s record length of ambient noise each, was merged to achieve a minimum of 5 minutes records at each measurement point (Khalil *et al.*, 2020).

For both cases, the data processing was done using the Geopsy software, developed by the SESAME European project (https://www.geopsy.org/) to obtain the HVSR curve from which the fundamental frequency and the amplitude of the peak were determined. Using the transfer function for a simple two-layer case, hard rock basement overlain by sedimentary deposits, with thickness h and velocity Vs, relationship between the fundamental resonance frequency and thickness h, is given as

$$f_0 = \frac{V_s}{4h} \quad (1)$$

With equation 1, the thickness of the overlying deposits can also be estimated if the shear wave velocity is known.


**Fig. 1:** Measurement points at Bukit Ledang, Malaysia.


**Fig. 2:** Measurement points at Lagos, Nigeria.

## Results and Discussion

Figures 3 and 4 shows the HVSR curve obtained from the analysis of the HVSR measurements from both sites. The curves were validated against the SESAME (2004) criteria ensuring the reliability of the fundamental frequency obtained from each curve. The fundamental frequency for Bukit Ledang (locations 1 – 4) is observed to range from 2.32 - 2.56 Hz, with an amplitude ranging from 2.41 - 4.96 (Table 1.0). Notably, the peak at measurement at location 2 is observed to be broad in nature, with a lower amplitude (2.6) as compared to other locations. This might be associated to the higher level of seismic noise observed in the measurements. However, reliability tests carried out on the peak showed that the $f_0$ is reliable and furthermore, it is within the range obtained for other locations.

For measurements points 5 to 8, in Lagos Nigeria, the fundamental frequency is observed to range from 0.85 - 1.29 Hz and amplitude ranging from 1.3 - 1.5. Although the picks are not as defined as in the other locations in Malaysia, which can be attributed to the duration of the measurements, the instrumentation as well the local geology, it still gives an idea of the general trend of the fundamental frequency of the area. Also of importance is the low amplitude HV curve (below 1), observed between the frequencies of about 1.5 to 10 Hz, which suggests the presence of a velocity inversion in the subsurface (Castellaro, 2016).Velocity inversion in this case is the decrease in the shear wave velocity with depth as against the expected increase in depth. The borehole logs obtained from UNILAG (Figure 5), shows the presence of organic clay from a depth of about 22 m – 32 m, which is below the sandy clay unit. Such velocity inversion can result in increased seismic

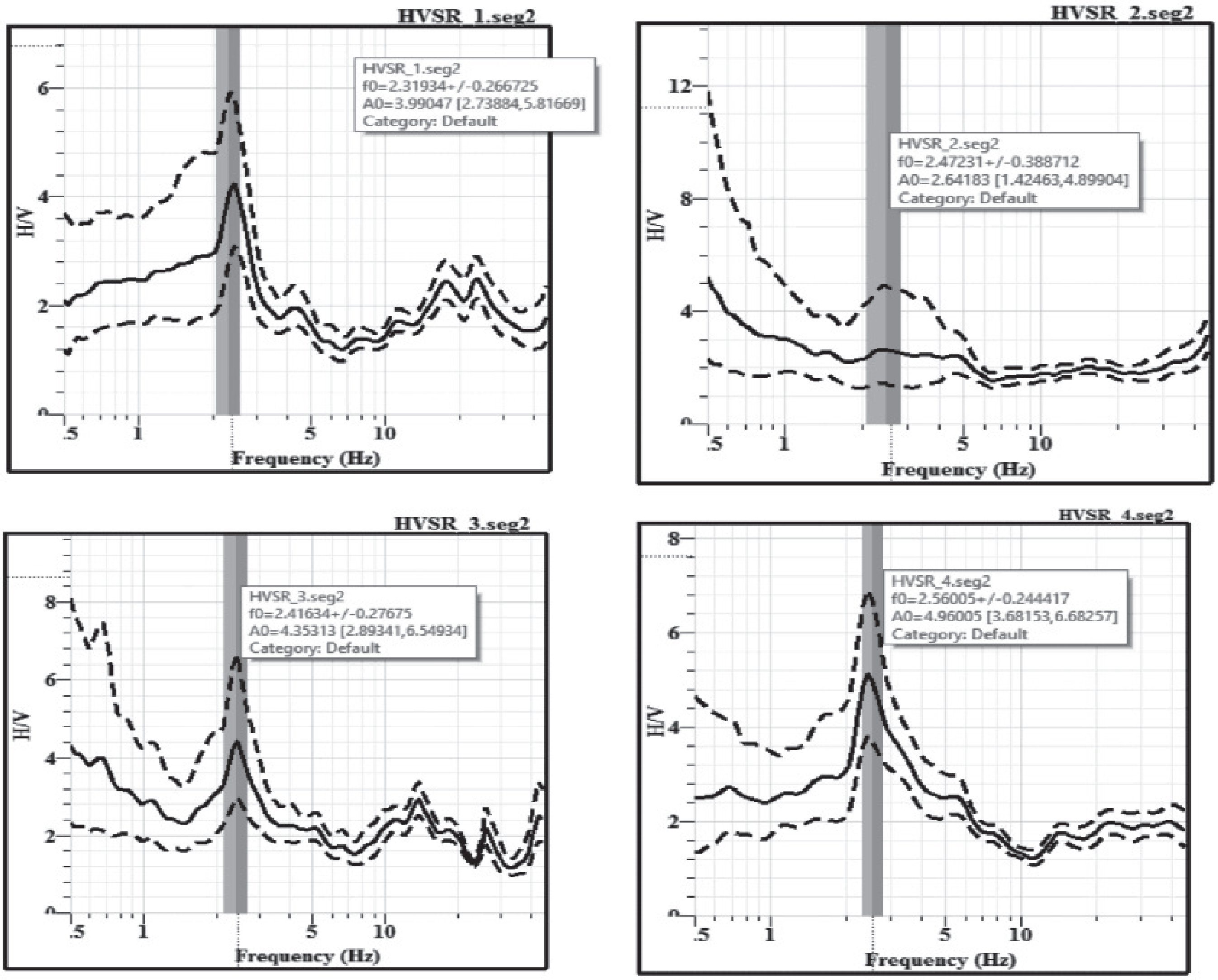


**Fig. 3:** The HVSR Curve for locations 1 to 4 (Bukit Ledang, Malaysia) showing the fundamental frequency and corresponding amplitude.

hazard, reduced foundation stability, high potential for soil settlement amongst others.

An estimate to the depth to impedance contrast at each location (seismic bedrock) was obtained using equation 1.0 and assuming an average Vs of the overlying layer of 220 m/s for Bukit Ledang and 120 m/s for Lagos, Nigeria. The Vs assumption was based on the values of Vs30 for different fundamental periods as classified by the National Earthquake Hazards Reduction Program (NEHRP) Site Classes (Building Seismic Safety Council (BSSC), 2001) (Table 2). It is worth noting that the use of the shear wave velocity has its limitations as the shear wave velocity of the site might vary due to local geological conditions. Also, vulnerability index indicating each location's susceptibility to structural damage due to ground motion was also estimated as highlighted by Nakamura (1997) using the equation

$$K_g = A^2/f_0 \quad \text{.........................................................(2)}$$

Where $f_0$ is the fundamental frequency and $A$, the amplitude associated with the $f_0$.

The vulnerability index obtained show higher values (>2.5) for locations in Ledang Malaysia, as compared to UNILAG, Nigeria. Higher vulnerability resonates site effects and can be used to assess potential liquefaction (Putti and Satyam, 2020). The values obtained thus suggests that Bukit Ledang is more susceptible to amplification effects and liquefaction as compared to locations in UNILAG.

The estimated fundamental frequency, period, amplitude, depth to impedance contrast, vulnerability index and NEHRP class for each measurement point is summarized in table 1.

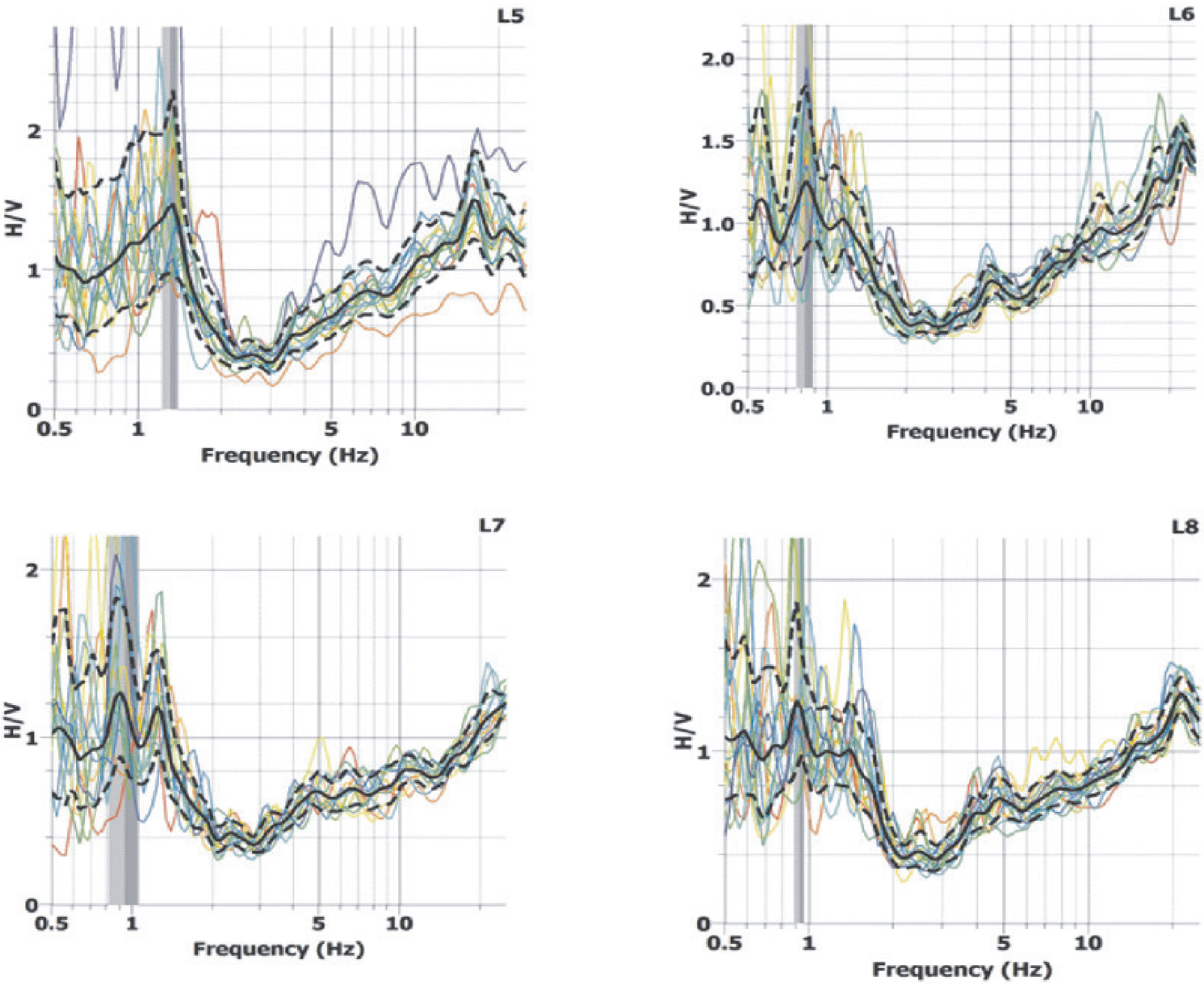


**Fig. 4:** The HVSR Curve for locations 5 to 8 (UNILAG, Nigeria) showing the fundamental frequency and corresponding amplitude.

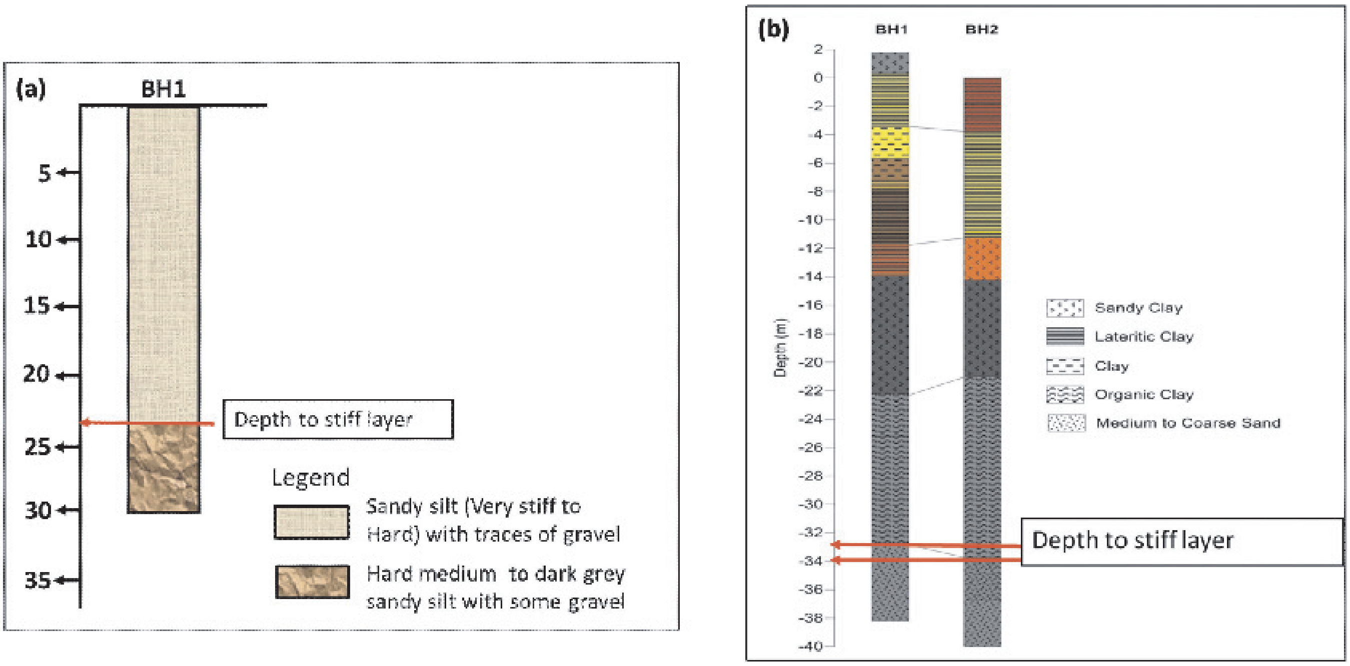


**Fig. 5:** Borehole log obtained for location (a) Bukit Ledang Malaysia (b) UNILAG, Lagos Nigeria

**Table 1:** Summary of the Results from the HVSR analysis

| Location | Fundamental Frequency (Hz) | Period (s) | Amplitude | NEHRP Site Class | Depth to Impedance Contrast (m) | Vulnerability Index |
|---|---|---|---|---|---|---|
| 1 | 2.32 | 0.4 | 3.99 | D | 21.55 | 6.86 |
| 2 | 2.48 | 0.4 | 2.64 | D | 20.16 | 2.70 |
| 3 | 2.41 | 0.4 | 2.41 | D | 20.75 | 7.85 |
| 4 | 2.56 | 0.4 | 4.96 | D | 19.53 | 9.61 |
| 5 | 1.29 | 0.78 | 1.5 | E | 23.26 | 1.74 |
| 6 | 0.85 | 1.18 | 1.3 | F | 35.29 | 1.99 |
| 7 | 0.91 | 1.10 | 1.4 | F | 32.97 | 2.15 |
| 8 | 0.92 | 1.09 | 1.3 | F | 32.61 | 1.84 |

**Table 2:** National Earthquake Hazards Reduction Program (NEHRP) Site Classes (Building Seismic Safety Council [BSSC], 2000)

| Site Class | Description | Natural Period | V30 Calculated from Site Period | NEHRP Site Classes |
|---|---|---|---|---|
| SC I | Rock | $T < 0.2\ s$ | $V_{30} > 600$ | A + B + C |
| SC II | Hard Soil | $0.2 \leq T < 0.4\ s$ | $300 < V_{30} \leq 600$ | C |
| SC III | Medium Soil | $0.4 \leq T < 0.6\ s$ | $200 < V_{30} \leq 300$ | D |
| SC IV | Soft Soil | $T \geq 0.6\ s$ | $V_{30} \leq 200$ | E + F |
| SC IV1 | | $0.6 \leq T < 1.0\ s$ | $120 < V_{30} \leq 200$ | E |
| SC IV2 | | $T \geq 1.0\ s$ | $V_{30} < 120$ | F |

Furthermore, using the results obtained, information about the soil structure analysis can be inferred. In the event of a vibration and or earthquake, the resonance phenomenon occurs when the fundamental frequency of the foundation soil coincides with the natural period of the building. Hence, building collapse is more likely if there is resonance phenomenon. Table 3 shows the natural frequency of different structures. The soil fundamental frequency for Ledang is greater generally greater than 2Hz, implying that there is a likelihood of soil – structure interaction for low rise buildings. In the case of UNILAG, the soil – structure interaction is more likely for high rise structures as the soil fundamental frequency is about 1.0 Hz.

**Table 3:** Natural Frequency and Its Impact on Infrastructure (after Nath, 2007)

| Type of Object or Structure | Natural Frequency (Hz) |
|---|---|
| 1 Storey Buildings | 10 |
| 2 Storey Buildings | 5 |
| 3-4 Storey Buildings | 2 |
| High Rise Building | 0.5 – 1.0 |

## Conclusion

The HVSR technique was utilized to provide information on the site fundamental frequency at different locations in Bukit Ledang, Malaysia and UNILAG, Lagos Nigeria respectively. The result indicates that the fundamental frequency ($f_0$) ranges from 0.85 to 2.56 across both locations, with locations in Bukit Ledang, showing a higher $f_0$. Fundamental frequency for both locations varies, with an average of 2.44Hz and 1.0 Hz for Bukit Ledang, Malaysia and UNILAG, Lagos respectively.

According to the NEHRP site classification, Bukit Ledang falls under class D (medium soil), while soils in UNILAG falls under site class E/F which implies that the soils in the area are soft soils with >3m soft silt or clay and might require a site specific evaluation. The HVSR curve for locations in UNILAG show amplitude less than 1 for a significant frequency range, which implies the presence of a low shear wave velocity layer (soft soil). The Vulnerability index suggests that soil in Bukit Ledang is more susceptible to amplification, when compared to UNILAG. Soil structure resonance is more likely to occur for low rise buildings in Bukit Ledang, while that of UNILAG is for high rise buildings.

In general, this study has successfully shown the effectiveness of the HVSR technique to obtain a good and reliable information about site effect parameters such as the fundamental site frequency. With this technique, criteria can be defined for new buildings to reduce the probability of soil – structure resonance that can result in collapse. The technique is suitable as a means of providing microzonation studies quickly and reliably which would be of great importance for both locations.

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