Soils and Rocks
An International Journal of Geotechnical and Geoenvironmental Engineering
www.soilsandrocks.com
ISSN 1980-9743
ISSN-e 2675-5475

Assessment of seismic vulnerability index of RAJUK area in Bangladesh using microtremor observations

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Case Study

Keywords
H/V peak amplitude
Frequency
H/V spectral ratio
Nakamura technique
Seismic vulnerability index

Abstract

Microtremor Horizontal to Vertical spectral ratio technique, also known as the Nakamura's method is growing in status for site response analysis. 500 locations in RAJUK area (1530 km^2) have been selected for microtremor observations. Microtremor data have been compiled and studied to estimate the predominant resonance frequency and *H/V* peak amplitude following the SESAME (2004) guideline. Finally, seismic vulnerability index of site soil using Nakamura's technique has been determined from predominant resonance frequency and *H/V* peak amplitude parameter. The calculated seismic vulnerability index for the studied 500 locations varies between 0.16 and 7.28. The low seismic vulnerability index (K_g) value means that the areas are relatively stiff and underlain by substantial deposit of sediments. The relatively higher K_g values are spread in the soft alluvial deposit areas. The areas with high K_g values are considered as fragile zones that may initiate significant damage to infrastructure situated in those areas during an earthquake.

1. Introduction

A large number of environmental studies have revealed that the majority of the Asian regions are exposed to seismic risks, which is mostly significant for South East Asia (Shah et al., 2018, 2019). Bangladesh has been damaged by great earthquakes in the past although it has not faced any significant great earthquakes in the recent years. In this region, most of the significant recent earthquakes have happened outside the important cities, and have damaged moderately less densely populated areas (Ansary & Rahman, 2013; Ansary & Arefin, 2020). Dhaka Metropolitan Development Plan (DMDP) area, which is mainly represented by RAJUK (Capital Development Authority) is the most populated city and the Capital of Bangladesh having a population of approximately 20 millions. Most of the policy makers and population do not recognize earthquake risk to be significant, although Bangladesh is situated in an area of major earthquake activity. It is a source of immense anxiety that significant damage to infrastructures may happen during a large earthquake occurring in this region.

Finn et al. (2004) has defined microzonation as the mapping of the earthquake hazards at local scales to integrate the effects of local geological environment. The term microzonation does not necessarily means a scale of mapping, while the prerequisite for defining local geological environment tends to state the more thorough scale maps (Roca et al., 2006). Building codes use the countrywide earthquake zonation maps in defining the minimum design requirements (DRM, 2004).

There are two sides of seismic safety: i) structural safety and ii) safety of a location based on the geotechnical conditions, such as site intensification, slope failures, and liquefaction. Effects of vibration have been taken care of in building codes all over the world to guarantee the safety of structures under seismic loading. Though, little attention in the form of land use guideline has been provided to the safety evaluation of individual sites (ISSMGE, 1999).

The purpose of the following review is to show the variety of methodologies applied for preparation of earthquake risk maps and the fundamental philosophies of zonation for ground motion with respect to diverse scales. Under this circumstance, necessary advancement is presented in the Manual for Zonation on Seismic Geotechnical Hazards, which is developed by the ISSMGE (1999). According to Mihalic et al. (2011), microzonation can be classified into three grades. Microtremor study together with simplified geotechnical studies have been placed in grade 2. Evaluation of ground motions is based on local seismicity, reduction of ground motion amount and local soil conditions. The local

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Submitted on September 6, 2020; Final Acceptance on April 16, 2021; Discussion open until August 31, 2021.
https://doi.org/10.28927/SR.2021.057420

soil condition is the most significant issue in defining surface ground motions. Therefore, evaluation of the soil conditions is based on the ranking of the zonation.

Among empirical methods for site response analysis, the popularity of HVSR (H/V spectral ratio method), also commonly known as the Nakamura's method (Parolai et al., 2001; Del Monaco et al., 2013) has been gradually increasing for the past three decades. The HVSR method is effective to estimate site response by removing source effects by dividing the horizontal component of ambient noise by the vertical component. This method has been applied by many researchers in many countries such as Mexico, Turkey, India, Pakistan, USA and Japan, to determine fundamental frequency, amplification and depth of basin (Qadri et al., 2015a, b, 2017, 2018; Rehman et al., 2016; Raymond, 2017; Singh et al., 2017).

The main aim of the paper is to determine the dynamic factors of alluvium including resonance frequency, resonance period, peak values of *H/V* ratio and seismic vulnerability index (*Kg*) at 500 locations of the RAJUK area using microtremor.

2. Geology of the RAJUK area

Dhaka is the capital, literary of Bangladesh; also it is the political and economic hub of the country. It is one of the most heavily populated cities in the South Asia. Microtremor observations have been carried out within the Dhaka city (around 250 km^2 area) by several researches (Ansary & Rahman, 2013; Ansary & Arefin, 2020; CDMP, 2009). In this research, the measurement sites will be selected within the entire Dhaka city and DMDP/RAJUK (Capital Development Authority) area (around 1530 km^2) (Figure 1). The use of microtremor investigation in this research is to estimate the seismic vulnerability index (K_g), by using the *HVSR* technique. The location of the 500 observation points is shown in Figure 2.

According to Reimann (1993), more than 80% of Bangladesh is underlain by Quaternary sediments consisting of deltaic and alluvial deposits of the Ganges, Brahmaputra and Meghna rivers and their tributaries. The sediments of Bangladesh geology have been classified into five major groups, which are Coastal deposits, Deltaic deposits, Paludal deposits, Alluvial deposits and Residual deposits. Dhaka is located between the Meghna and Brahmaputra Flood Plains. Forty four boreholes are drilled in the first stage of geotechnical field investigation along with the field microtremor investigation as shown in Figure 3 to get an overall idea of the soil profile of RAJUK/DMDP area. Figure 4 shows the lithology of the east – west cross-section between borehole numbers 20 to 185 and Figure 5 shows the lithology of the north – south cross-section between borehole numbers 400 to 62. The Madhupur Clay Residuum is the main soil deposit in the top (which is part of Pleistocene terrace deposit: very stiff soil shown by red color in Figures 4 and 5) and then Alluvial Sand, Silt and Clay and their various combinations. According to the CDMP (2009), the engineering bedrock of Dhaka city (Shear-wave velocity $\geq$ 400 m/s) is situated around 70 m below the existing ground level.

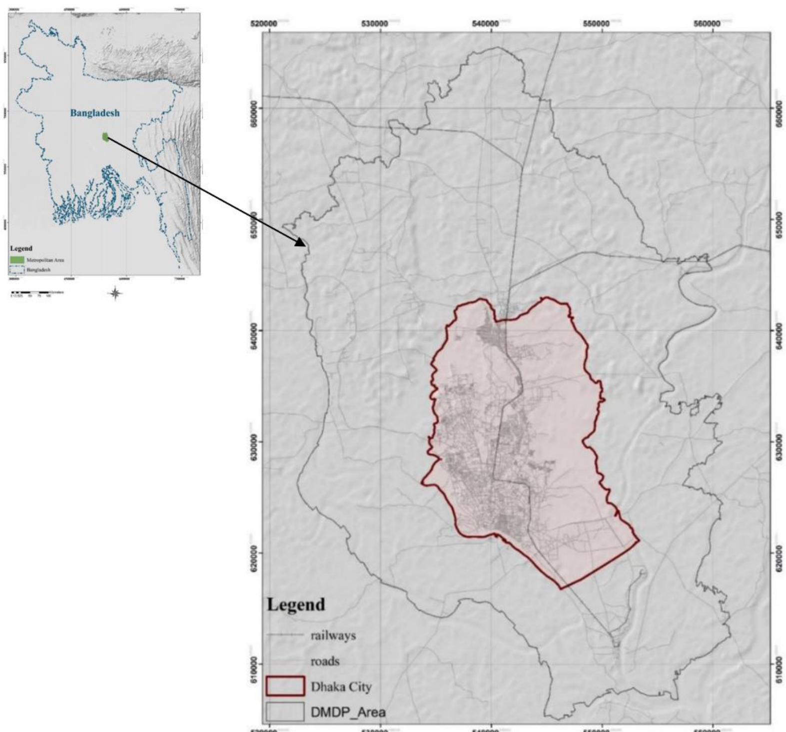

Figure 1. RAJUK/DMDP area with respect to the country Bangladesh.

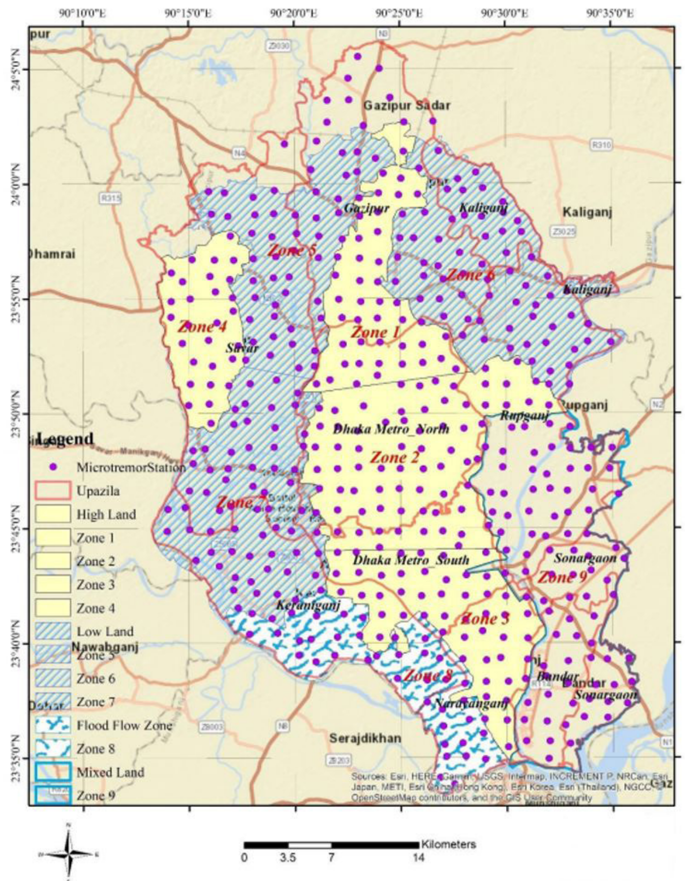

Figure 2. Location of the microtremor observation point within RAJUK area.

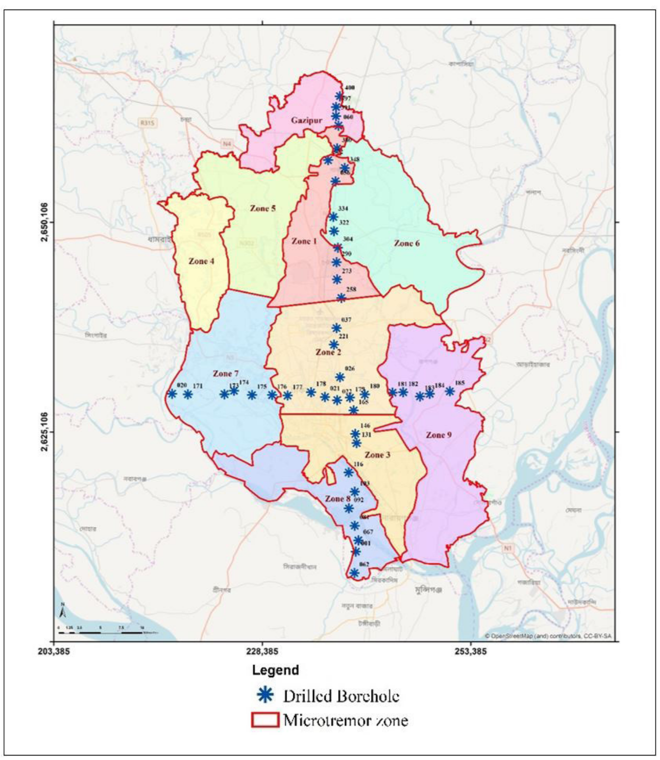

Figure 3. Location of 44 drilled boreholes for phase 1 of field investigation.

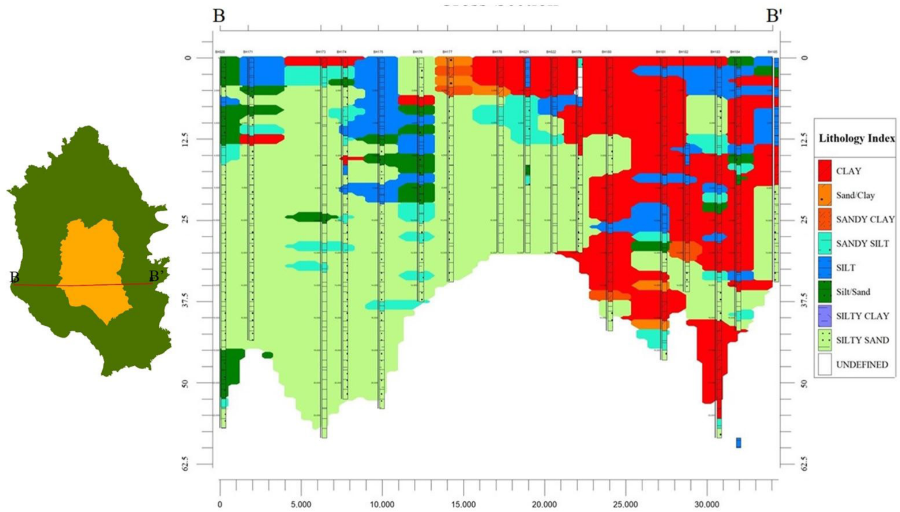

Figure 4. The lithology of the east-west cross-section between boreholes no. 20 to 185.

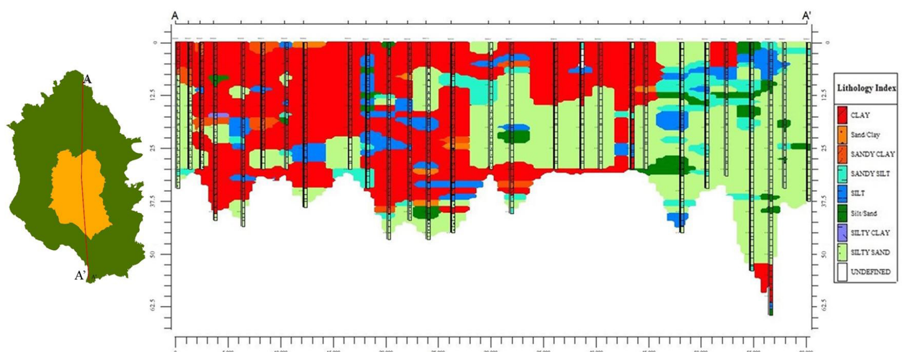

Figure 5. The lithology of the north-south cross-section between boreholes no. 400 to 062.

3. Microtremor survey method

The microtremors are generated by the movement of machinery in industries, vehicles, pedestrian, the flow of water in rivers, rain, wind, deviation of atmospheric pressure, and oceanic waves. The majority of the sources of microtremors generally originate from human activities.

Ambient noise has been put into use to glean information of the soil amplification since 1950s. Nogoshi & Igarashi (1970, 1971) are among the first to implement the horizontal to vertical spectral ratio (HVSR) to microtremor measurements, however the practice of this technique has faced many condemnation due to the uncertainty about microtremor sources. Many researchers (Ansary & Arefin, 2020; Qadri et al., 2015a, 2017; Raymond, 2017; Singh et al., 2017) have paid a renewed interest for estimating dynamic properties of soils and structures using microtremor, since lucid and dependable information can be obtained by very easy and less costly noise measurements.

Nakamura has developed the *H/V* technique for various geological site environments in Japan along with borehole investigations, as well as with the analysis of strong ground motion. It has been assumed that the vertical component of ambient noise that maintains the uniqueness of source to sediments of the ground surface is comparatively biased to Rayleigh wave on the sediments. Thus, the vertical component can be applied to eliminate the Rayleigh wave and the source effects from the horizontal components. On soft ground, vertical motion is smaller than the horizontal motion. On stiff ground, vertical and horizontal vibrations are comparable to each other both on the value and shape. Horizontal to vertical ratio has been estimated from each maximum value and has been judged against the softness of ground and the *H/V* peak amplitude. For this reason, the value of horizontal to vertical ratio greatly matches with these soil characteristics. The *H/V* spectral ratio shows the amplification characteristics by the multiple reflections of the *SH* wave at least around F_0, the predominant frequency of sedimentary layer, and shows the characteristics has been baffled by the Rayleigh wave around $2F_0$. Where the effect of the Rayleigh wave is smaller, it is possible to determine preliminary as well as the secondary peak of amplification due to multiple reflections with the *H/V* spectral ratio.

H/V technique has been regularly applied in seismic microzonation investigation due to its relatively small cost. The main feature of the *H/V* method is its stability: an identical result may be found if one replicates measurements for a week (Volant et al., 1998), after a month (Mucciarelli & Monachesi, 1998) or after a year (Bour et al., 1998). This method is most useful in determining the natural frequency of soft soil sites where there is a large contrast with the underlying bedrock. The technique is particularly suitable in locations of reasonable seismicity, due to the lack of considerable seismic recordings, in contrast to high seismic regions.

The main suggested application of the *H/V* method in microzonation studies is to delineate the fundamental period of the location and assist limit the geotechnical and geological models used for numerical estimations. *H/V* method, alone or collectively with other techniques, has been used for the seismic zonation of many cities.

The *H/V* technique has been established to be helpful to determine the fundamental period of soil deposits. However, measurements and the study should be executed with care. The endeavor of this study is to obtain the increase of ground motion over as broad a frequency range as possible, for the elastic (low-deformation) soil behavior as well as compute the natural frequency.

4. Data collection and analysis method

Within the RAJUK area, at 500 locations, microtremor observations have been done as shown in Figure 2. A standard square network with approximately 1.7 kilometers sides has been considered; one station has been placed within each square.

4.1 Data acquisition

Microtremor data have been gathered on three-component sensors of GS11D Geospace Technology. The system has an internal 12V rechargeable battery having the ability to record 5 hour continuously. Surveys have been carried out at 100 samples per second for about 20 minutes. Figure 6 shows a GS11D sensor with an internal 12V rechargeable lead battery connected to a laptop. All the data have been collected during night time.

Figure 6. Setup illustration of GS11D sensor with an internal 12V rechargeable lead battery connected to a laptop.

4.2 Analysis of the data and development of the *H/V* curve

All 500 microtremors have been recorded as three components velocity data. In order to obtain *H/V* ratio from the recorded microtremor data, Geopsy software has been used with a 21-s time window. In order to reduce the effects of the noises and obtaining the best possible results, a band pass filter between 0.05 to 6 Hz is implemented on the records. H/V ratios have been estimated eliminating the time windows infected with transients (after Qadri et al., 2015b, 2017) often associated to built-up sources or other noises. A conventional approach to detect the infected transients is based on a comparison between the short-term average (*STA*) and the long-term average (*LTA*). The *H/V* computation has been applied to only those windows with an STA/LTA ratio lying between 0.20 and 2.50. A Konno & Ohmachi (1998) filter and cosine taper with 5% width have been applied to every window to smooth the Fourier amplitude spectra along with a coefficient of 40 for bandwidth. The waveform of microtremor record in station 23 is shown in Figure 7.

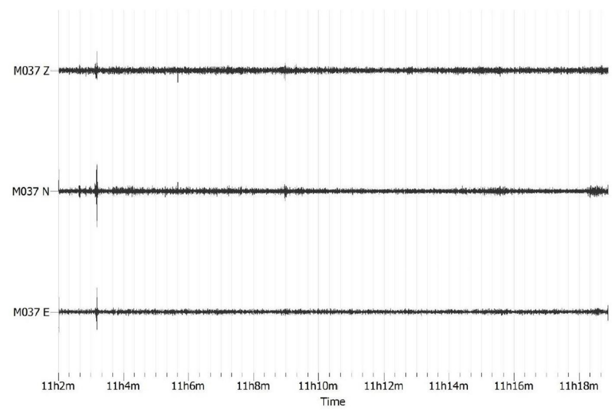

Figure 7. The microtremor component's waveform in the station 23.

This method estimates *H/V* ratio of the ambient noise which has been observed at a single point. *H/V* ratio is the proportion between the Fourier amplitude spectra of the horizontal (*H*) to vertical (*V*) components. For computing this ratio, the first step is to record the ambient signal using a three-component system; the next step is to pick the most stable time windows; then for each time windows, estimate the Fourier amplitude spectra by smoothing; then average the two-horizontal component (using a quadratic mean); in the next step for each window, *H/V* ratio is estimated; finally, the average *H/V* ratio is estimated. European Commission (2004) parameters and criteria have been used in order to obtain a reliable *H/V* curve.

The *H/V* method is applied to obtain the resonance frequency and the *H/V* peak amplitude. The curves derived from all the records are shown in Figure 8. To avoid the effect of probable environmental noises, time windows can be selected in Geopsy software. The *H/V* technique is applied on the selected windows. The selected windows and the graph after noise removal in station 23 are shown in Figure 9 and Figure 10 respectively. The assessed parameters including resonance frequency, *H/V* peak amplitude and vulnerability index in station 23 are presented in Table 1. Figure 11 shows *H/V* curves for six more stations.

4.3 Comparison of microtremor data with 1D response analysis using the program shake

From the existing borelogs, and PS-loggings, soil model at each site has been established for theoretical analysis. The transfer function of the shear wave (the surface motion versus the incidental motion at depth) has been calculated using the soil models. Figure 12 shows the four typical graphs for comparison of amplitude ratio between the transfer function of shear wave and microtremor *H/V* ratio. The 1D response analysis using the program SHAKE has helped to estimate the characteristics transfer function curve. Microtremor *H/V* ratio graph has been obtained from the Horizontal to Vertical spectral ratio (*H/V*) of Fourier spectra as discussed earlier.

These figures show that the amplitude values of the ratios and the predominant resonance frequency for the two cases slightly vary. The cause of this variation is that microtremor is composed of various types of waves, but the theoretical transfer function is based on shear-wave only.

5. Results and discussions

The microtremor investigations have been conducted at 500 locations within the RAJUK area. The location of every station has been determined by hand held GPS. Around twenty minutes of data acquisition has been done on average when the noise level has been low. The outputs of the study have been presented in the form of resonance frequency, *H/V* peak amplitude and seismic vulnerability index distribution within the RAJUK area.

5.1 The resonance frequency

The resonance frequency has been classified from less than 0.23 Hz to more than 6.6 Hz (0.23-7.67). The resonance frequency distribution within RAJUK area has been presented in Figure 13. Most areas of RAJUK show the resonance frequency of less than 1.2 Hz. It means that, the RAJUK is mostly covered by soft soil with a high resonance period. It should be noted that, to avoid the resonance phenomenon during a major earthquakes, the number of building floors should not be consonant with the resonance period of the soil.

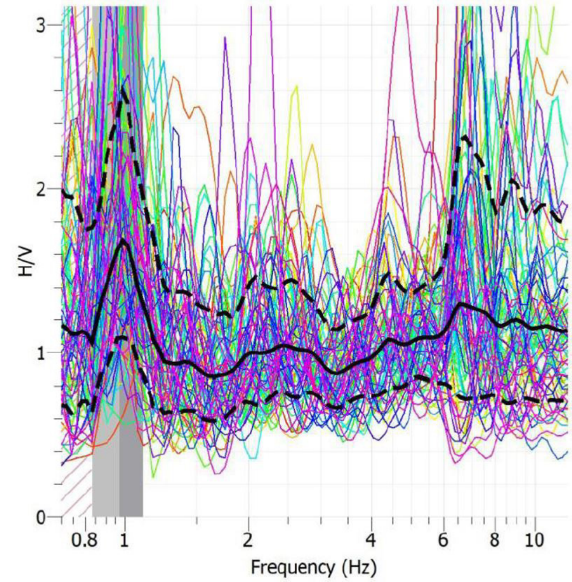

Figure 8. The plot of H/V curve for all records in the station 23.

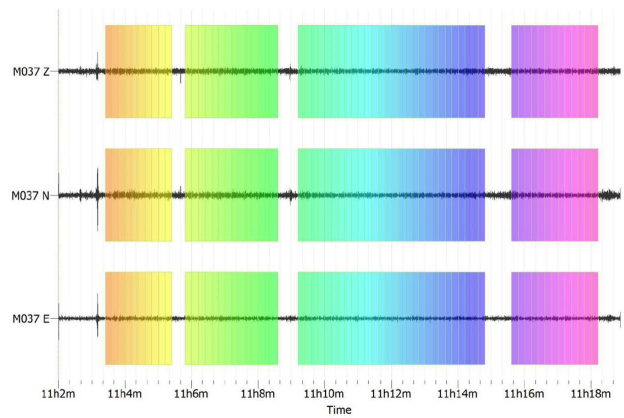

Figure 9. The selected windows from station 23 record.

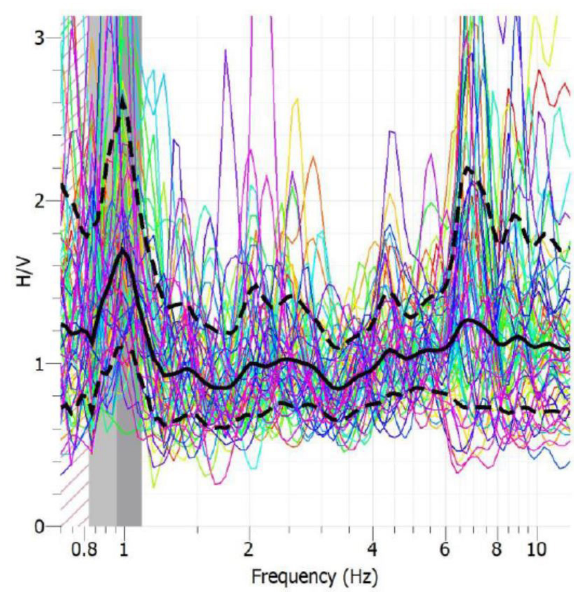

Figure 10. The plot of *H/V* curve after noise removal at the station 23.

Table 1. The results of *H/V* graph for station 23.

Station No.	Longitude	Latitude	Resonance Frequency f_0 (Hz)	*H/V* Peak Amplitude (A_0)	Resonance Period (s)	Vulnerability Index ($K_g=A_0^2/f_0$)	Remarks
23	90.4372	23.6236	0.96	1.64	1.04	2.80	low

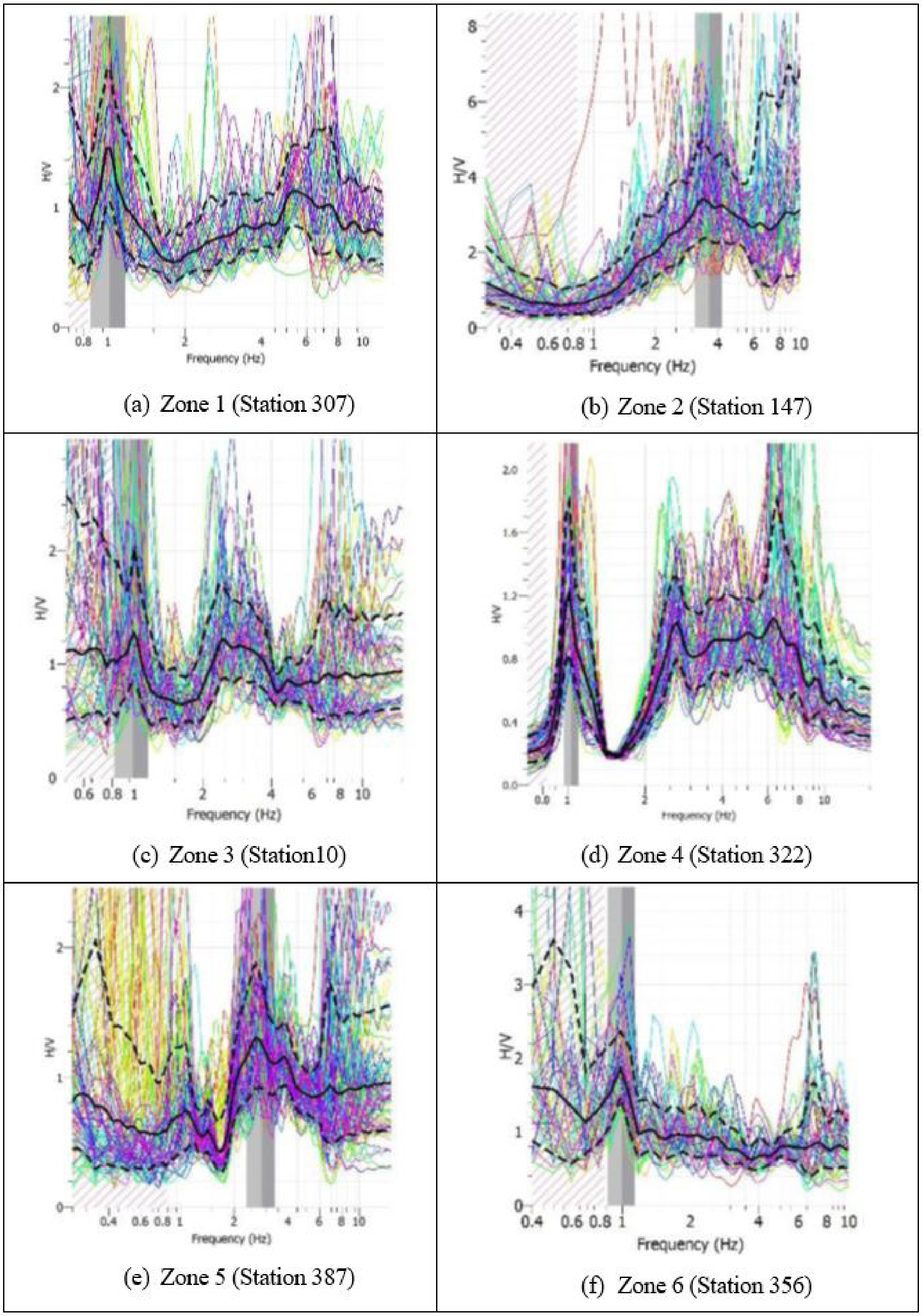

Figure 11. The H/V graphs for several stations located in different zones of Dhaka city.

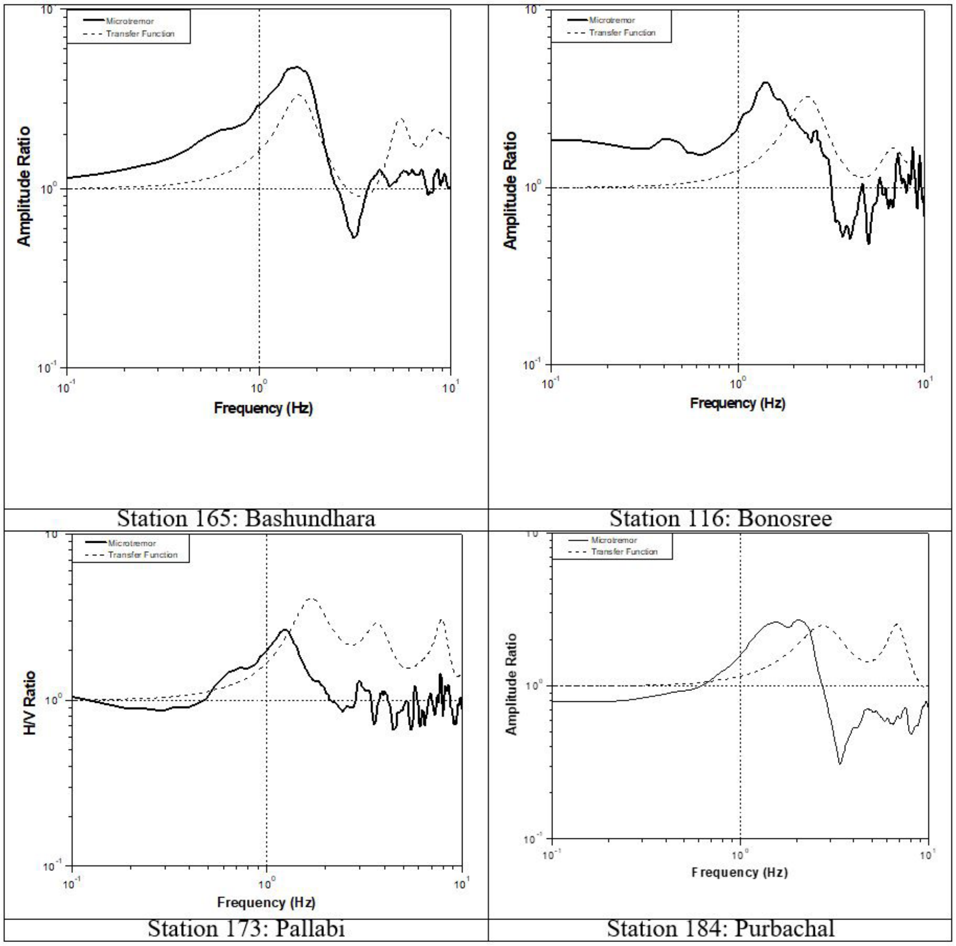

Figure 12. Comparison of *H/V* peak amplitude of microtremor and theoretical transfer function from numerical 1D response analysis for various locations in Dhaka city.

A minor part of RAJUK area shows high resonance frequencies. These anomalies are mostly observed in the middle part and some areas of the northern part of RAJUK area. The remarkable point of the distribution of high-frequency areas in RAJUK area is its compatibility with the local geology; these areas are underlain by Pleistocene terrace deposits (Ansary & Arefin, 2020) which are also represented by red Madhupur clay deposits in Figures 4 and 5. Therefore, the areas with high frequency probably consist of compact soils where the land subsidence rate is low (Higgins et al., 2014). The high frequency (low period) areas can be used for high-rise constructions considering the local geotechnical properties (such as lateral spreading, *H/V* peak amplitude, and liquefaction).

5.2 *H/V* peak amplitude

The *H/V* peak amplitude is classified from around 0.85 to more than 4 (0.85-6.54). Figure 14 shows the H/V peak amplitude variation within RAJUK area. Fortunately, most parts of RAJUK area show a *H/V* peak amplitude around 1. Consequently, the probability of soil amplification during an earthquake is not very high. Anyhow, there are areas with *H/V* peak amplitude of more than 1 which need special attention in designing the development plan. The most areas with a high *H/V* peak amplitude locate in the middle part of the city where, unfortunately, most of the constructions have been already placed.

5.3 Seismic vulnerability index

Seismic vulnerability index (*Kg*) is a parameter which shows the level of vulnerability of a soil layer to collapse. Therefore, this index is useful for identifying areas that are relatively weak during incidence of seismic events. Nakamura (2000) have demonstrated that a high-quality correspondence exists between seismic vulnerability index (*Kg*) and the distribution of damage due earthquakes. This index can be estimated by squaring from the peak value of *HVSR* curve and dividing it by the value of the predominant frequency. Four major classifications of the seismic vulnerability index have been recommended, these are Low (0–5), Moderate (6–10), High (11–20), and Very High (>20).

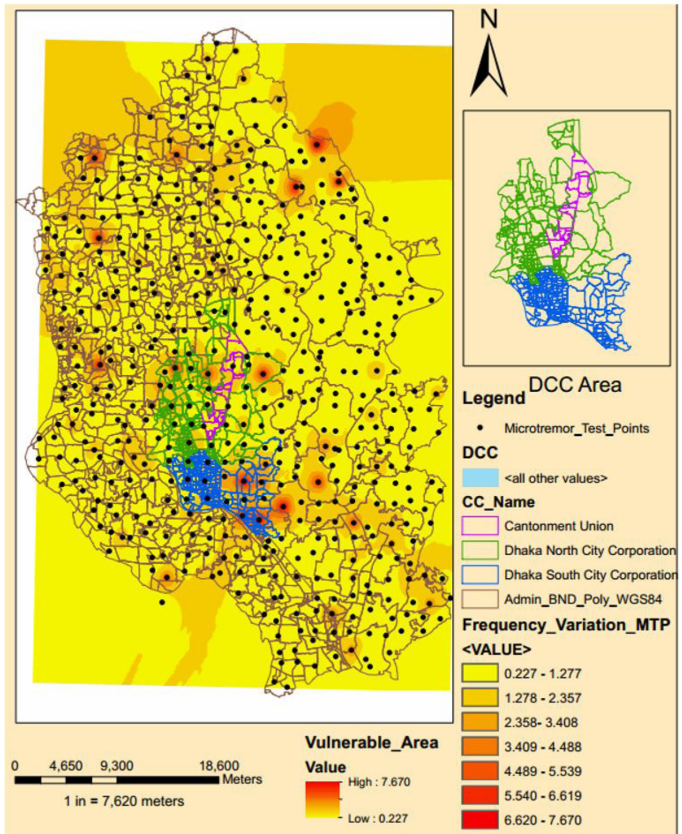

Figure 13. Resonance frequency variation in RAJUK area.

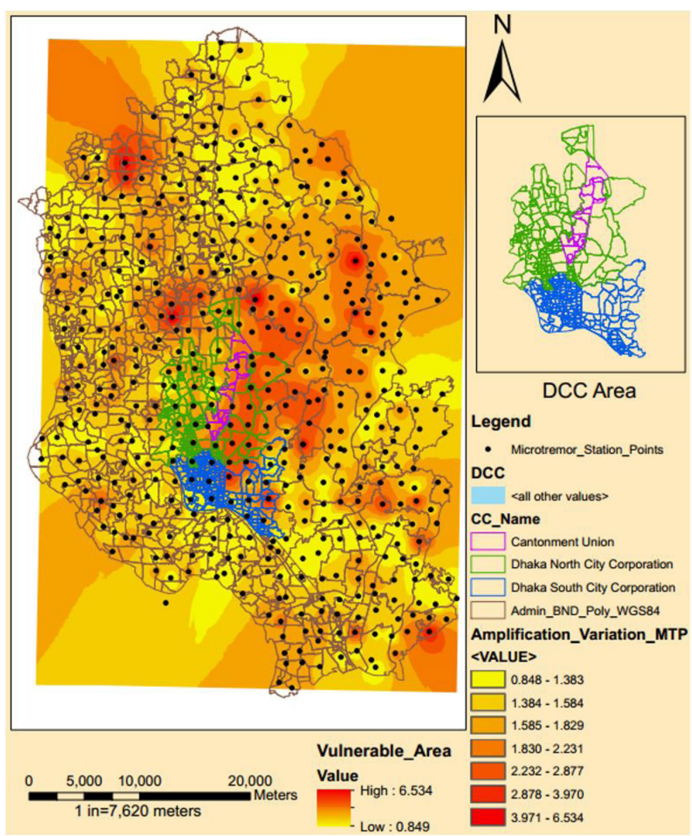

Figure 14. *H/V* peak amplitude variation in RAJUK area.

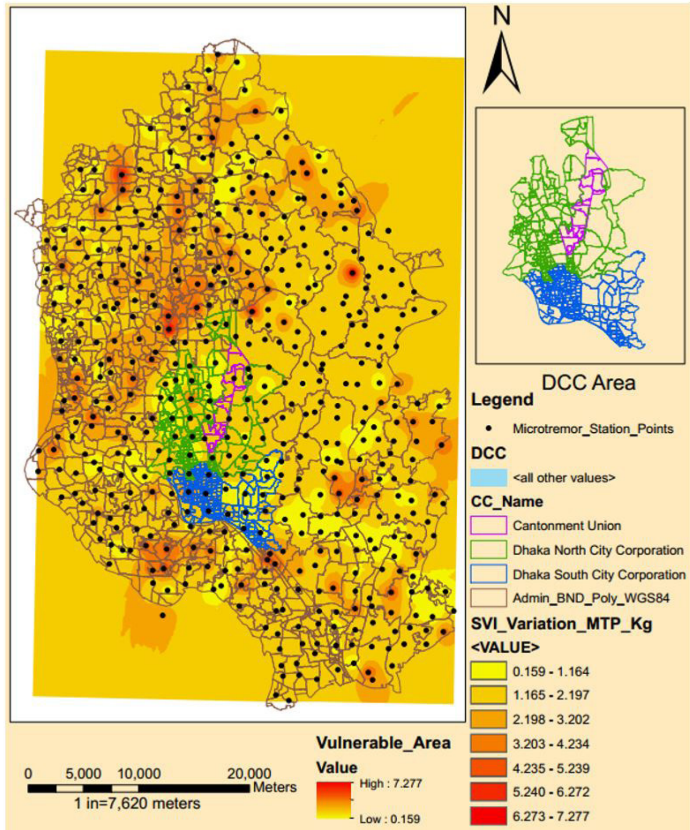

Figure 15. Seismic vulnerability index variation in RAJUK area.

The seismic vulnerability index is classified from around 0.16 to more than 6 (0.16-7.28). Figure 15 shows the seismic vulnerability index variation within RAJUK area. Fortunately, most parts of RAJUK area show low seismic vulnerability index. Consequently, the probability of soil amplification during an earthquake is not very high.

6. Conclusions

This is the first time 500 microtremor observations have been conducted within the RAJUK area. The locations are selected considering the flood plains, restricted areas, roads, and sensitive centers. The findings of this research have been presented with respect to resonance frequency, *H/V* peak amplitude and seismic vulnerability index distribution. The predominant frequencies within RAJUK area are comparatively homogeneous, ranging from 0.23 to 7.67 Hz. In most of the soft soil locations, the frequencies are low and in a few stiff soil locations, the frequencies are high. The *H/V* peak amplitude or peak of *H/V* spectral ratio in investigation sites vary from 0.85 to 6.54. For stiff soil sites, small spectral values are observed and for soft soil sites, high spectral values are observed. The seismic vulnerability index varies between 0.16 and 7.28. The small seismic vulnerability index signifies that the areas are relatively stiff as well as underlain by thick sediment deposit. The findings of microtremor observations can be applied as an input for a lot of investigations, for instance the site selection of geotechnical boreholes or designing the city development plans, etc.

Declaration of interest

On behalf of all the authors, the corresponding author states that there is no conflict of interest

Author's contributions

Abdul L. Helaly: conceptualization, data collection, methodology. Mehedi A. Ansary: Writing- reviewing and editing.

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List of symbols

K_g seismic vulnerability index
H/V horizontal to vertical ratio
f_0 Resonance frequency
A_0 H/V Peak Amplitude