Earth Systems and Environment (2020) 4:439–454
https://doi.org/10.1007/s41748-020-00158-6

ORIGINAL ARTICLE

Evaluation of Site Effects Using HVSR Microtremor Measurements in Vishakhapatnam (India)

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Received: 26 August 2019 / Accepted: 25 May 2020 / Published online: 6 June 2020
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Abstract

Dynamic soil properties form an important base for estimation of strains and deformations due to dynamic loading. Frequency, amplitude and time period are the prominent parameters that define a strong ground motion. When the frequency of the soil and strong ground motion reaches to same value during a seismic event, it results in resonance effect leading to huge damage of the structures. Therefore, it is required to estimate the predominant frequency of the soil and amplitude of vibration. Invasive and non-invasive techniques can be employed to determine the dynamic soil properties. Invasive methods, including SPT, DCPT, downhole, cross hole, etc., contain source located either on the surface or in a downhole. The non-invasive methods can be classified as single station and multiple source methods. Microtremor method has been gaining a lot of importance due to its feasibility to perform test in densely populated areas and the speed of processing the information. The instrument works on the principle of recording micro-vibrations in the ground of specific amplitude termed as microtremors. Therefore, evaluation of site effects has been attempted using microtremor testing in Vishakhapatnam (India). The city of Visakhapatnam is one among the prominent and largest functional port cities of India. Site effects due to sand and clay soil layers are characteristic of the whole city area. Seismic hazard studies of the study area are required as per the survey by Disaster Management Authority of India (NDMA 2012). The microtremor horizontal-to-vertical spectral ratio (HVSR) method was therefore applied for measuring the free-field response in the city to assess the peak frequency and amplitude of the soil sediments. Nakamura (A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. Railway Technical Research Institute/Tetsudo Gijutsu Kenkyujo, Tokyo, 1989) method has been used to analyses the recorded data as it simplifies the recording process and provides accurate results. It has been evident from the results that clear H/V spectral ratio peaks were observed in the entire central parts of the city, whereas in the eastern and western parts lower site response has been observed due to low impedance contrast of gravel with the rock. The predominant frequency hazard map shows frequency distribution of 0.43–10 Hz throughout the city. Frequency is considerably higher in the central part (> 4 Hz) than in the eastern and western parts (> 1 Hz) in the north eastern and south western locations.

Keywords Microtremor · Site effects · HVSR · Spectral ratio · Frequency · Amplitude

1 Introduction

Low-amplitude vibrations in the range of 10^{-4}–10^{-2} caused due to artificial sources are termed as microtremors. Microseisms and microtremors can be categorized from the frequencies and the type of origin. Microtremors are caused due to man-made activities and have frequencies > 1 Hz. Microseisms are caused due to oceanic activity, local meteorology, winds, etc., and have frequencies < 1 Hz. In the present scenario, microtremors gained prominence in evaluation of dynamic characteristics of the soils such as resonant frequency and amplitude. From the analysis of records from multiple sensors of same site, shear wave velocity and

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thickness of the soil sediments can be estimated. Kuo et al. (2009) have concluded that microtremor recordings are efficient in evaluation of shear wave velocity by comparing three different methods. The reliability of H/V spectral ratio approach has been reviewed by various researchers by comparing their results from the analysis with records of strong ground motion (Chávez-García and Cuenca 1996; Chávez-García and Tejeda-Jácome 2010; Manne and Neelima 2013).

Microtremor survey can be carried out in two different methods, i.e., standard spectral ratio method (SSR) and HVSR method (Nakamura 1989). Though both HVSR and SSR methods provide reliable results (Diagourtas et al. 2002), HVSR method (Nakamura 1989) has an advantage. It does not require any reference site for recordings. Identification of a reference site near every test location is laborious and will be a herculean task when the testing is to be performed in dense cities. Hence HVSR method is chosen in the present research.

In this study, microtremor testing has been performed in Vishakhapatnam city to generate frequency and amplitude maps for the city. Though the city has no record of significant earthquakes, it has been considered for detailed seismic evaluation by the NDMA. In case of sites with low range of seismic events, microtremor testing is the best to demonstrate the site response (Hardesty et al. 2010). Therefore, this method can be adapted in urban cities such as Vishakhapatnam with moderate to low range of seismic events.

2 Geological and Seismicity of the Study Area

Visakhapatnam is located in Andhra Pradesh state, India, and extended in 160sq.km area. The city extends between the coordinates of 17° 40′–17° 45′ N and 83° 11′–82° 20′ E. The population of the city is about 17 million (2011 Census). Of the total occupied area, the major land is of urban usage of which 66% is used for residential and commercial purpose, 20% by industries and rest by wetlands. The eastern part of the city is populated densely and covered with residential area. The topography of Visakhapatnam is undulated characterized by the hill ranges of Eastern Ghats on all sides except eastern boundary which is limited by Bay of Bengal. The hills are occupied by deciduous forest with thick soil cover. The eastern boundary constitutes upland sloping towards Bay of Bengal at a height of 65–75 above MSL. Kailasagiri hill range acts as northern boundary of the city, whereas the Yarada hill range acts as southern boundary. Few hillocks with portions of low land and a huge tidal basin separate the two hill ranges. Narava Gedda is the largest stream passing over the city towards salt marshland from northwest. The city consists of major minerals such as Charnockites, Khondalites, quartzites and pegmatites (Fig. 1).

60% of Indian landmass is considered to be prone to earthquakes. The area of study lies in the Stable Central Region (SCR) of Peninsular India. From past case histories of Jabalpur earthquake (1997) and Latur earthquake (1993), all regions of India are prone to earthquakes. Though Visakhapatnam does not consist of any major faults, abundant number of lineaments covers the area. The city is classified under seismic zone II (IS 1893:2016) susceptible to a PGA of 0.1 g. About 108 seismic events (1817–2018) have been identified in about 300 km radius of the city ranging from a magnitude of 2.1 to 6.0. Conversely, the regions which lack previous seismic history are assumed to be prone to excess seismic risk. Therefore, the seismic hazard of the city is proposed to be estimated in this paper. The parameters that quantify seismic hazard such as frequency and amplitude are proposed to be estimated using microtremor testing and the analysis is done using Nakamura (1989) technique.

2.1 Geotechnical Details

Around 50 deep boreholes data at 30 different locations were collected for the further analysis. From the collected geotechnical data and geology of the considered city, it is observed that gravel clay and gravel loams along with sandy clay and sandy soil are the major soil types available. Red clays are predominant and gravelly clay occupies the next place. Corrected standard penetration (N_c) values are in the range of 3–100 throughout the city. Shear wave velocity (V_s) ranges from 120–500 m/s at various locations. The above soil characteristics indicate the presence of soft marine clays at few locations near the port area of Vishakhapatnam. Rock outcrops have been identified at some locations including MVP colony, Durga Nagar, and Yarada. Visakhapatnam contains intrusive igneous meta-sediments along with igneous rocks characterized by Precambrian age. Younger red soils are found to 9 m depth. Representative borelogs at few locations have been presented in Fig. 2. Khondalites capped by laterites and dune sands along with concentrations of black sands along the coast were also found throughout the city. Clayey soils with percentages of sand particles ($< 30\%$) and silt and clay particles (< 0.075 mm) are also found in the coastal areas. These soils have coefficient of permeability $< 10^{-7}$cm/sec. Mechanical analysis of sands along the coast line and red gravels that are predominant is presented in Table 1.

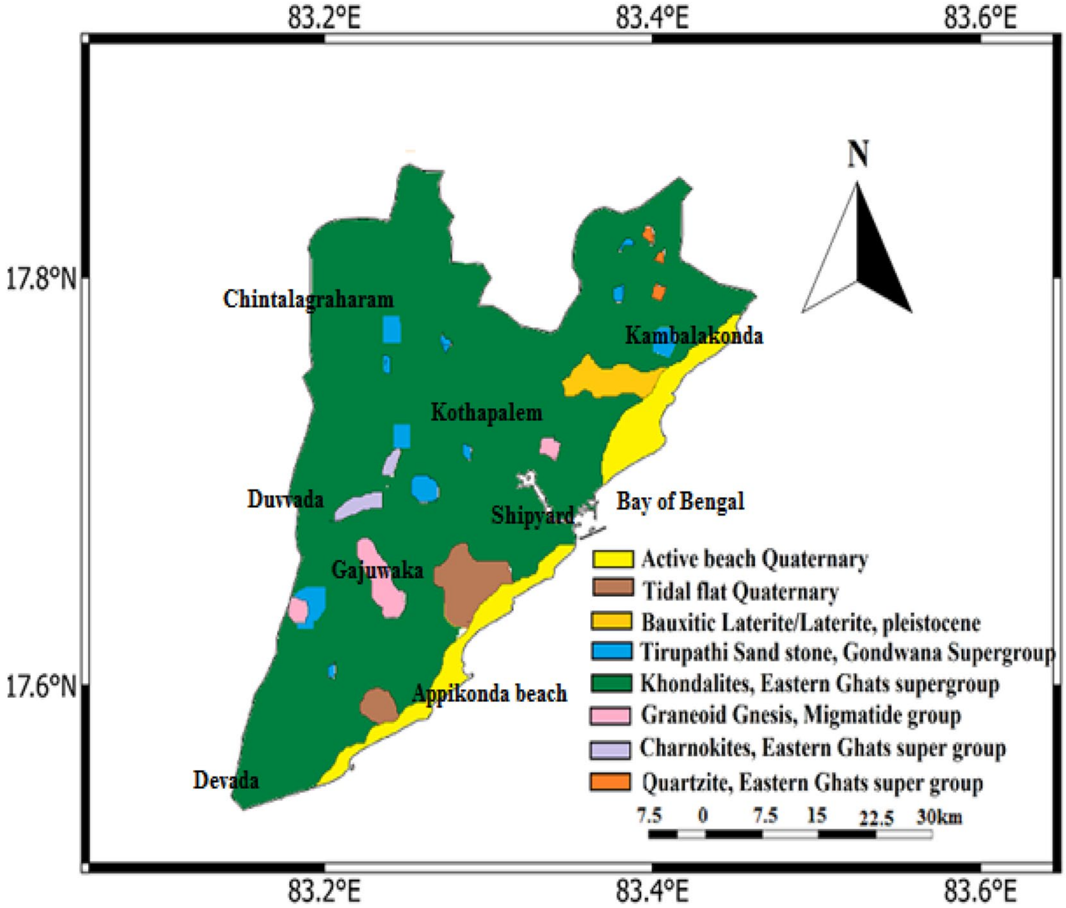


Fig. 1 Geology Map of Visakhapatnam (Modified from Ratnakar et al. 2015)

Ground water level in the study area varies between 3 and 14 m (from G.L) (Fig. 3). The water levels in bore wells are up to a maximum of 35 m. The eastern and northern parts of the city consist of deeper water levels (> 6 m depth) below ground level, whereas southern and western parts have water levels at depth of 3 m to 6 m below ground level. The ground water table levels in the western parts of the city can be attributed to the flow of Narava Gedda stream.

3 Microtremor Testing

The microtremor testing technique can be described as an analog of electrically passive magneto-telluric exploration (Asten et al. 2004). Microtremor survey can be carried out either by using single station-based or array-based (ReMi) approach. Array-based approach is used for correlating shear wave velocity resulting in estimation of soil sediment thickness (Manne and Satyam 2012) and requires multiple sensors. Single station technique is elementary and can be used to evaluate the predominant frequency, amplification factor and vulnerability index of the study area. Estimation of dynamic characteristics of soil using microtremor has been very common in the 1980s. But the SSR method that was used requires a reference site very near to the site of interest which is not feasible in all environmental and geological conditions. The HVSR method has been introduced by Nakamura (1989) which gained prominence. Though both the methods provide accurate results (Diagourtas et al. 2002), HVSR method has an advantage. It does not require recordings at reference site. Identification of a reference site near every location of testing is difficult and is intricate when the testing is performed in dense cities (Putti et al. 2019). Since 1989, the method has been applied to study dynamic properties and for microzonation of several cities (Caracas-Venezuela (Duval et al. 2002); Dinar-Turkey (Ansal et al.

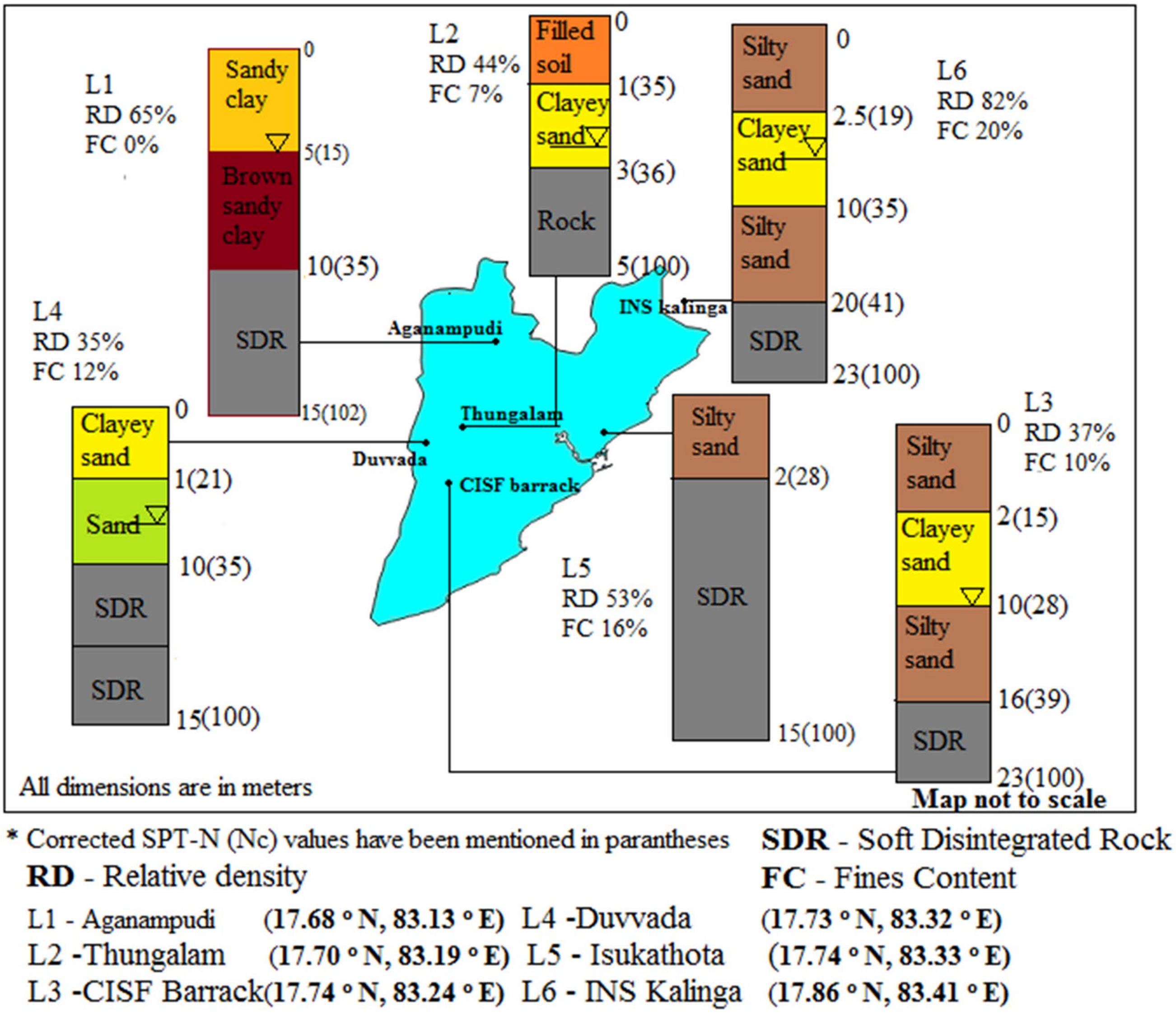


Fig. 2 Representative Borelogs at few locations in Visakhapatnam

Table 1 Mechanical analysis of soils in Visakhapatnam

S. no	Property	Value		
1	Location	Rushikonda (17.79° N, 83.38° E)	Maddilapalem (17.73° N, 83.32° E)	Bheemili (17.88° N, 83.44° E)
2	Specific gravity	2.5	2.78	2.65
3	Grain size analysis			
	Gravel Size (%)	0	73	0
	Coarse Sand Size (%)	0	14	80
	Medium sand size (%)	7	4.9	5.1
	Fine sand size (%)	91.8	5.1	4.6
	Fines (%)	1.2	3	6
4	Plasticity characteristics			
	Liquid limit (%)	–	31	–
	Plastic limit (%)	–	19	–

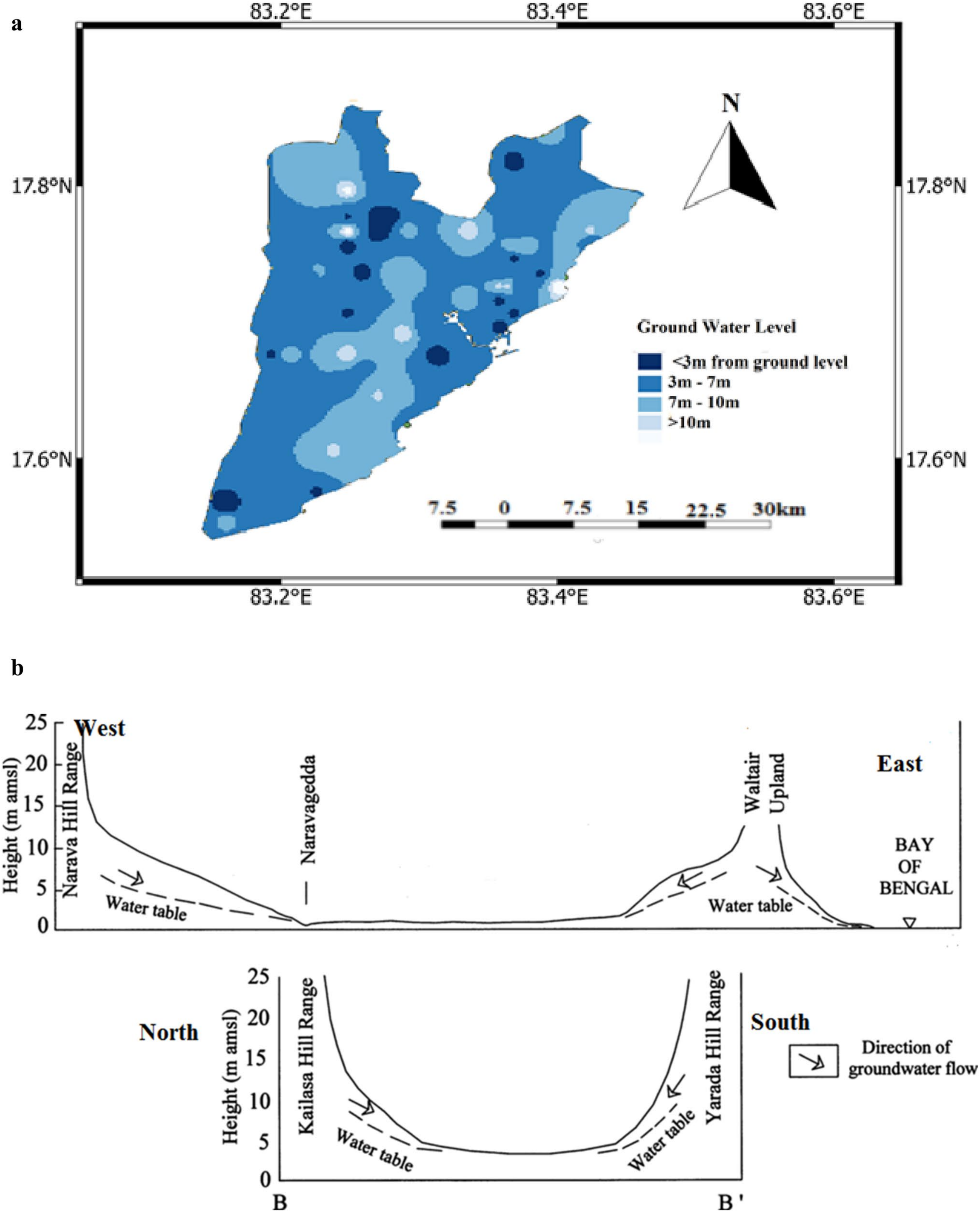


Fig. 3 **a** Groundwater map of Visakhapatnam city, **b** Direction of groundwater flow in the study area (Modified from Subbarao 2008)

2001); Southeastern Iran; Lower Manhattan-New York (Stephenson et al. 2009); Marmara region-Western turkey (Hasancebi and Ulusay 2007); Hong Kong (Pappin et al. 2012); Izmir-Turkey (Eskişar et al. 2013); Egypt (Mohamed et al. 2013)). Apart from these applications microtremor has been used to map collapsed columns in coal mines (Pei-Fen et al. 2009) and for estimation of seismic motion along expressways (Maruyama et al. 2000). Surve and Mohan (2010) conducted microtremor testing in Mumbai to demarcate the reclaimed area and actual basaltic islands from the resonant frequencies. Vulnerability index (Kg) from microtremor can be obtained by dividing the square of amplitude with peak frequency. The index can be used to identify liquefiable sites. Supporting evidence has been provided from case histories (Rao and Satyam 2005; Hardesty et al. 2010; Huang and Tseng 2002; Saita et al. 2012). The most important steps in applying Microtremor survey are acquisition of data, processing and analysis of data. The intricate part of the study is the data analysis. Crucial information regarding the noise source and test site is available from the frequency–amplitude response spectrum (Neelima and Towhata 2016). Clear peaks in the frequency plots infer distinct impedance between upper soft layer and the bedrock. Lower peaks at higher periods are usually imperative of hard rock. Clear peaks at higher frequencies indicate that the sediment is indicative of weathered soil overlying rock. Single and distinct peaks are observed in the response spectrum when the source is at a distance of 3 to 50 times the layer thickness. Two peaks show up in case of distant source. Pappin et al. (2012) from their study in Hong Kong area inferred that the measured frequency values match the calculated values when the soil profile is considered up to a values where SPT N > 100. The limitation of using single station microtremor is that it is not reliable when the local geology is complex and ground response is not due to single-impedance contrast (Chávez-García et al. 2007).

Microtremor recordings have been conducted in 75 locations distributed throughout the city. For the recordings to be performed without any disturbance, a suitable location has been selected such as open ground away from buildings, obstruction, wind, underground structures. During daytime the ambient noise is high and this affects the amplitude of vibration. So, recordings have been done at early morning and late evenings. If such disturbances are not avoided, the recorder records microseisms instead of microtremors. The recording setup (Fig. 4) consists of a triaxial velocity sensor (MS 2003+), Recorder (MR 2002-CE) and field laptop. The sensor has to be placed on a levelled ground to avoid baseline error. The noise has to be recorded for duration of 1 h with pre-event and post-event time of one second. GPS system has been used to record the coordinate of the site. Two horizontal and vertical component recordings (for HSVR analysis) have been made at locations stretching from Bheemunipatnam to Mutyalammapalem. The test locations in the present study are as shown in Fig. 5.

Fig. 4 Instrument setup at test location (Tenneti park)

3.1 Analysis and Results

Frequency–amplitude spectrum has been produced from vector sum of the vertical and horizontal ground motions individually at each location using Fourier transformation. For the clear recognition of peak, the curves have been smoothened up to 20%. Each spectrum has been individually examined to obtain the predominant ("resonant") frequency for the corresponding location. The peak frequency from the spectra indicates the thickness of soft sediment overlying stiffer materials.

The city has been characterized into three main zones depending on the type of the soil, predominant frequency values, shear wave velocity, SPT (N_c) (corrected) and plot trend (Table 2). Figure 6 shows predominant frequency—H/V amplitude response spectra of different locations according to the proposed classification. Hazard maps have been generated for the study area with respect to predominant frequency and H/V amplitude classifying the city into three major zones as shown in Figs. 7 and 8.

3.2 Vulnerability Index

Nakamura (1996) has proposed vulnerability index (Kg) value for evaluating earthquake damage of surface ground and structures precisely. H/V amplitude and predominant

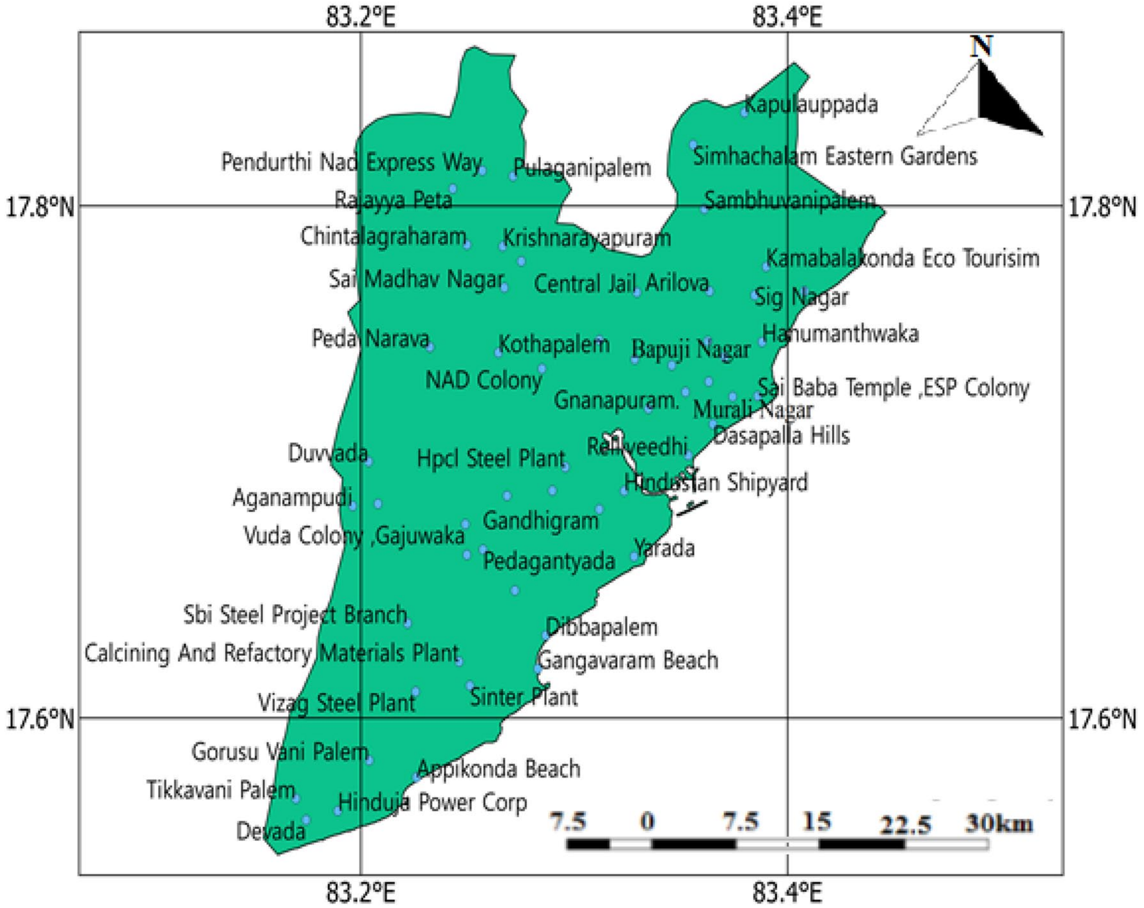


Fig. 5 Location of microtremor tests carried out in the study area

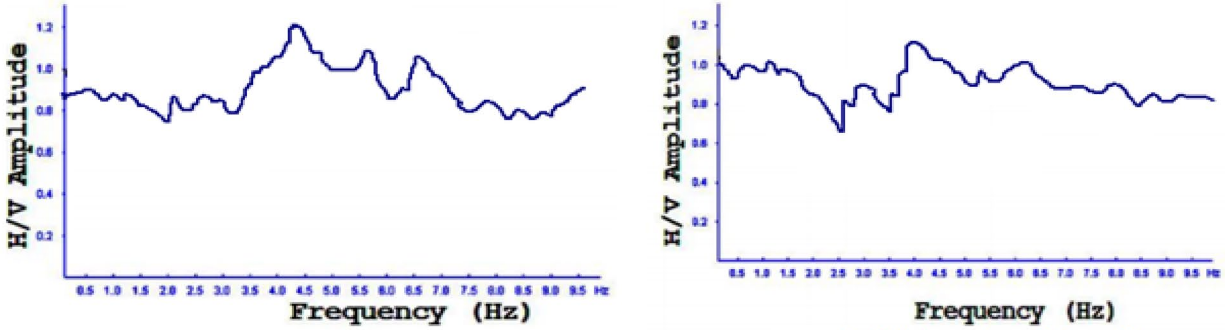
Table 2 Proposed site classification

S. no	Proposed soil class	Predominant frequency (Hz.)	Type of the soil	Corrected SPT (N_c)	Shear wave velocity (m/s)
1	T-I	>4.0	Disintegrated rock, Gravel sand, Gravel with pebbles,	≥ 40	≥ 310
2	T-II	2.0–4.0	Red moorum, Sandy silts, Silty sand, Clayey sand,	14–39	200–310
3	T-III	<2.0	Soft marine clays, Silty clay, marine soils	≤ 15	≤ 200

frequency from microtremor testing are used to calculate the vulnerability index. Earthquake damage can be correlated through Kg by relating ground amplification and peak frequency of the soil sediments (Satyam 2006). Vulnerability index, Kg, can be calculated using the relation:

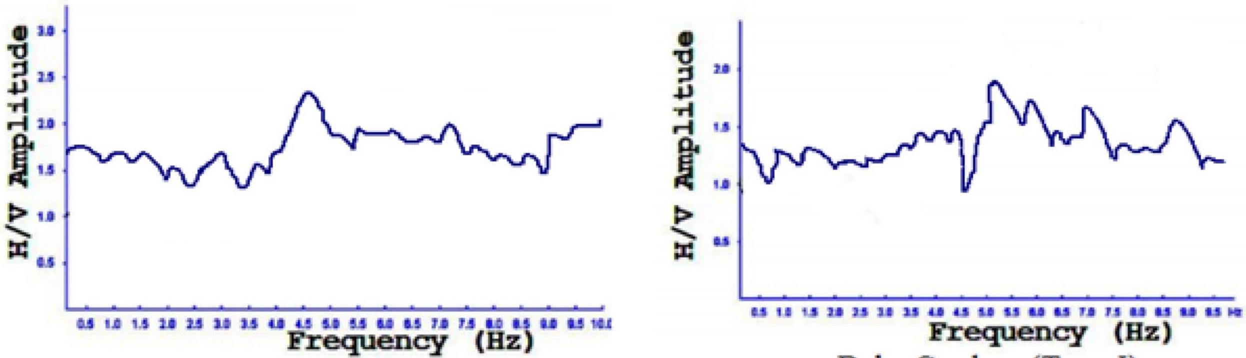
$$K_g = A^2/f \tag{1}$$

where A is the amplification factor and f is the peak resonant frequency from microtremor survey using HVSR technique. Vulnerability index resonates the site effects and can significantly correlate past damages in an active seismic region and can also be used to assess potential liquefaction hazard associated with the study area. Huang and Tseng (2002) concluded that the higher vulnerability index is observed in the locations where the chance of liquefaction is certain. From the liquefaction assessment of the Vishakhapatnam, it was clear that many places in eastern and north western parts of the city have certain chances of liquefaction (Putti and



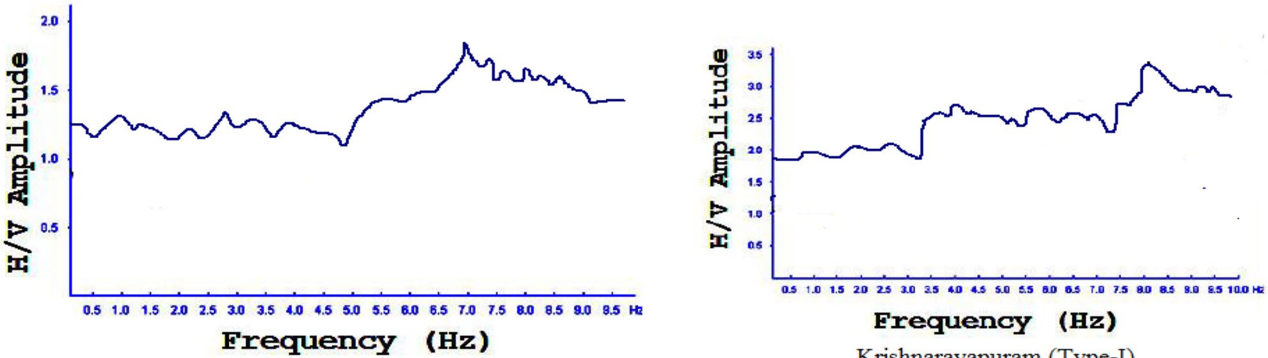
Bapuji Nagar (Type-I)

Calcining plant (Type-I)



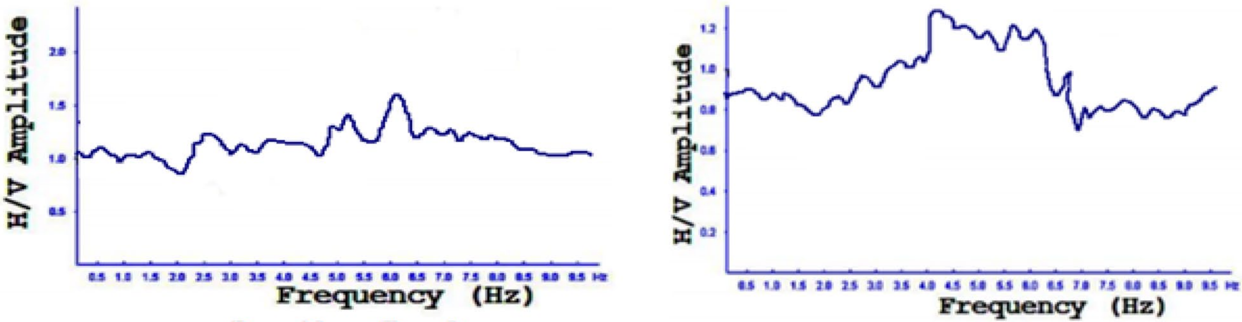
Gandhigram (Type-I)

Daba Gardens (Type-I)



Nattayapalem (Type-I)

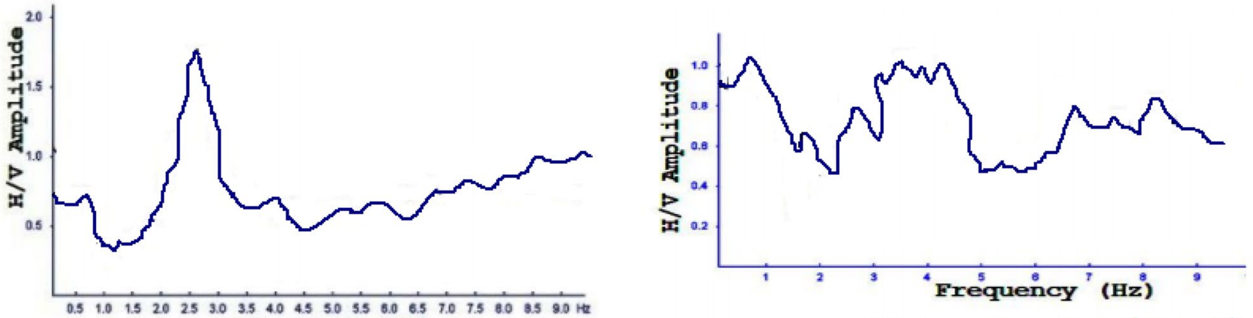
Krishnarayapuram (Type-I)



Durga Nagar (Type-I)

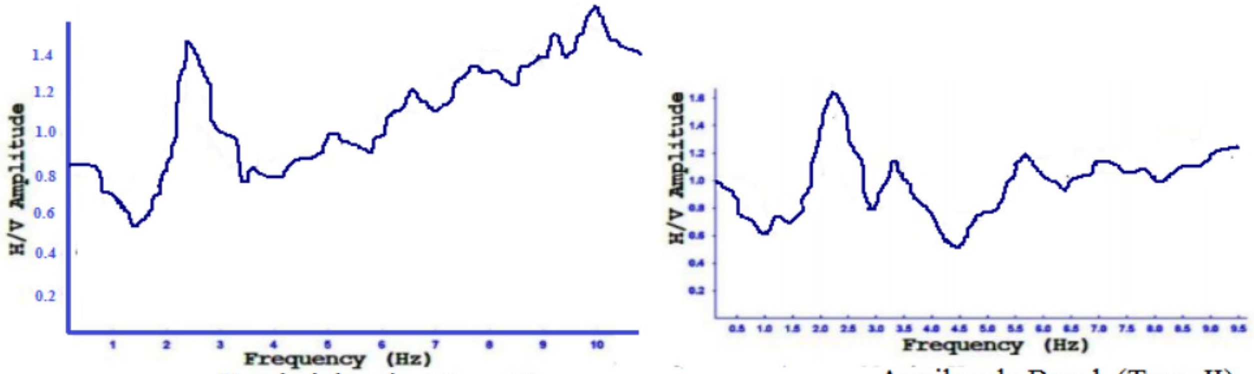
Chinthalagraharam (Type-I)

Fig. 6 Frequency–amplitude response spectra of different classes for few locations



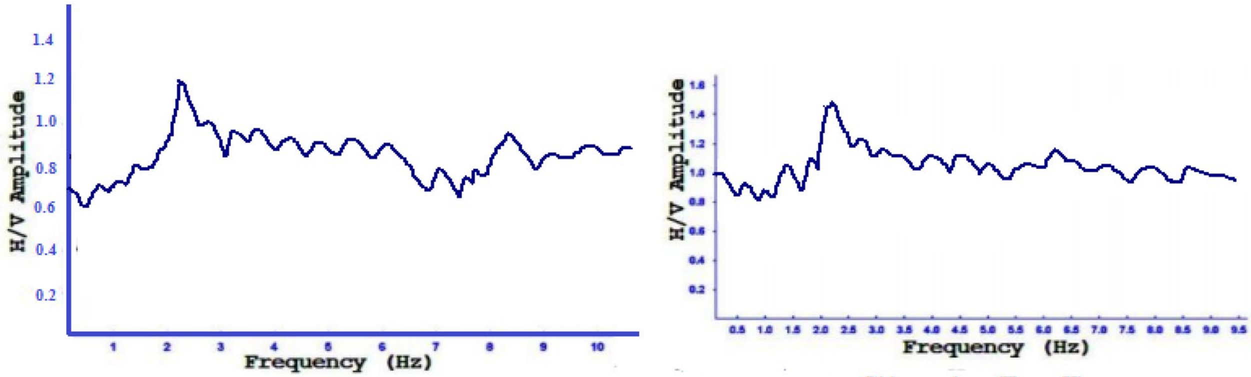
Pedagantyada (Type-II)

Mudurasalova Park (Type-II)



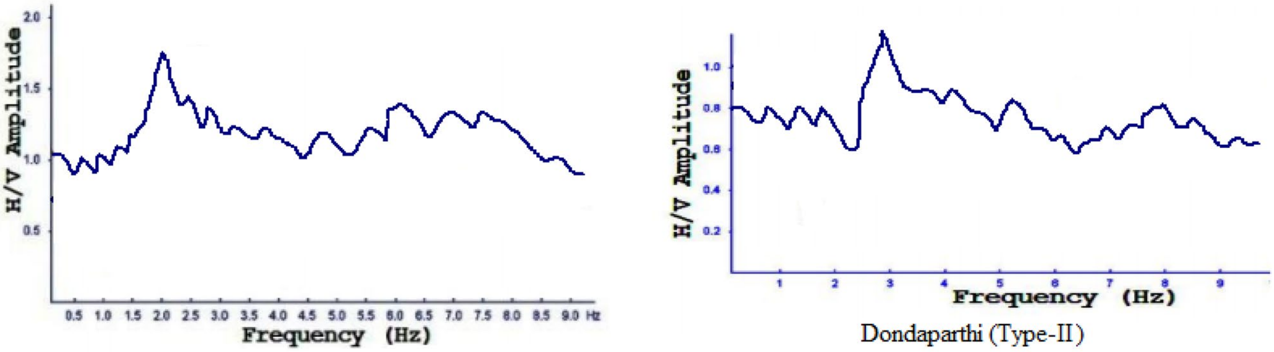
Kambalakonda (Type-II)

Appikonda Beach (Type-II)



Kalinga Nagar (Type-II)

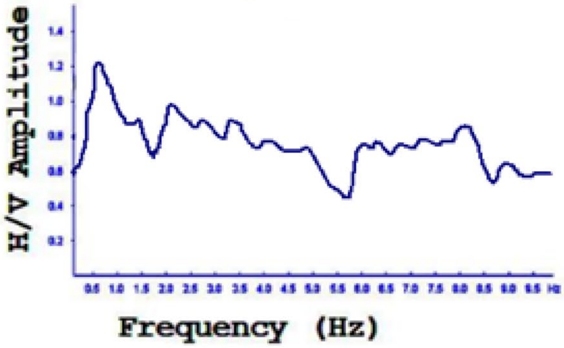
Chinnapalem (Type-II)



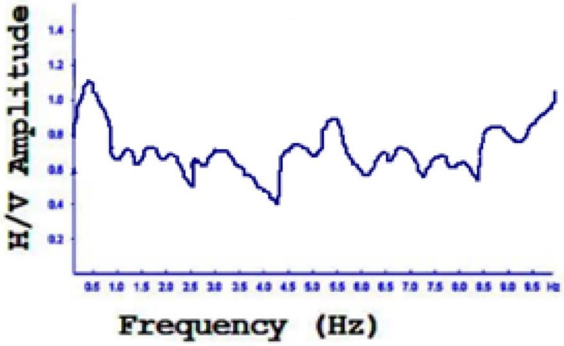
Devada (Type-II)

Dondaparthi (Type-II)

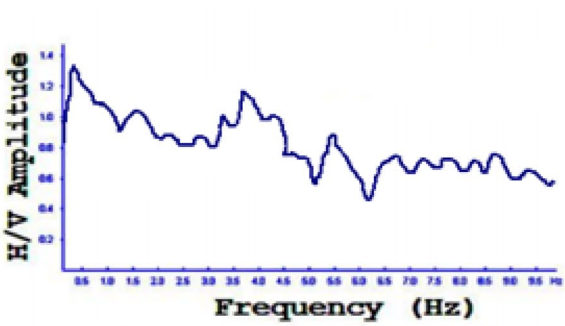
Fig. 6 (continued)



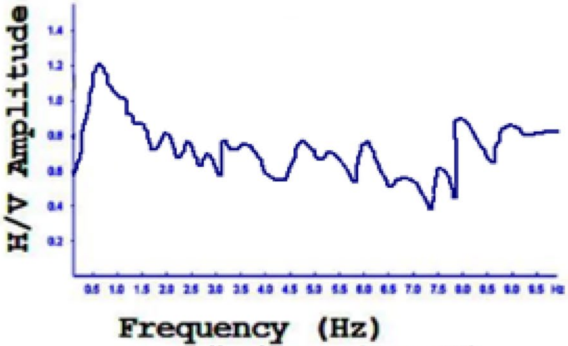
Dwaraka Nagar (Type-III)



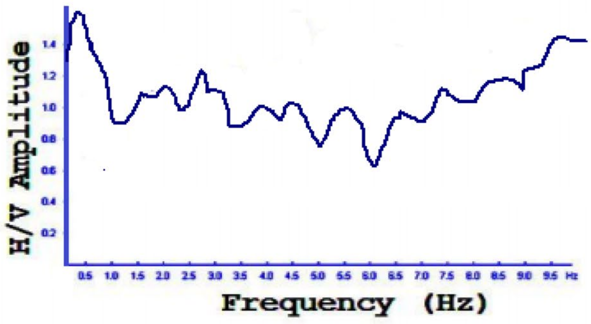
Srinivas Nagar (Type-III)



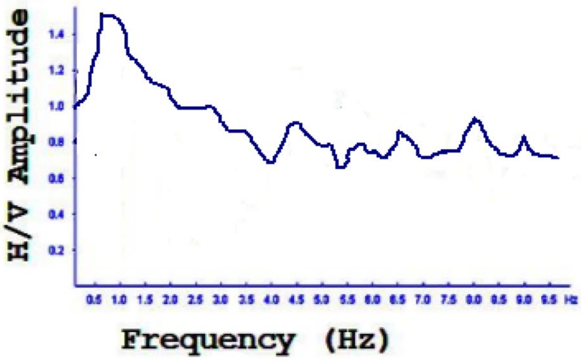
Gangavaram Beach (Type-III)



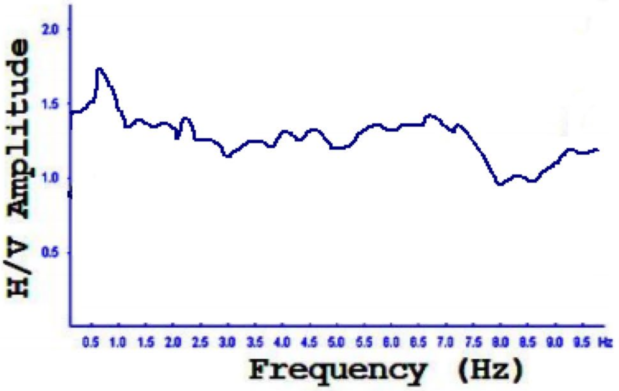
Sriharipuram (Type-III)



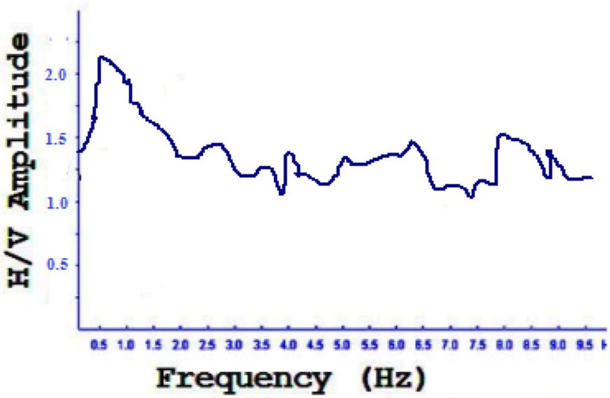
Rajayyapet (Type-III)



NTR centre (Type-III)



Arilova (Type-III)



Seshadri Nagar colony (Type-III)

Fig. 6 (continued)

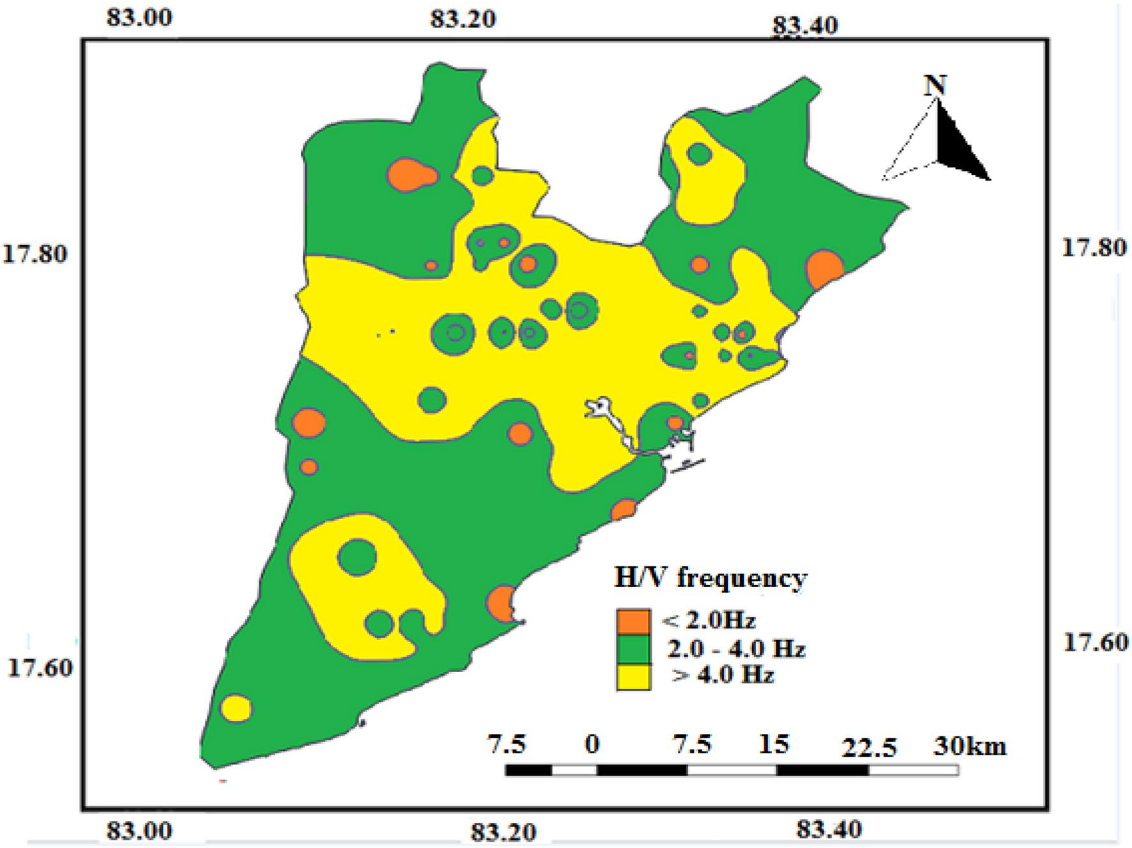


Fig. 7 Peak frequency map of Vishakhapatnam

Satyam 2018). So, an attempt has been made to estimate the vulnerability of the soils in the city using the Nakamura method and it has been observed that a good match has been found with the liquefaction hazard map of the area. The hazard map in terms of vulnerability index has been prepared from the analysis as shown in Fig. 9.

3.3 Relation Between Depth and Resonance Frequency

Predominant frequencies observed at 35 locations (with available bore logs) among all the test locations have been fitted nonlinearly with depth of bed rock. Peak frequency is a widely used parameter in estimating the thickness of soil sediment. Nakamura (1989) stated that various relationships are available to correlate predominant frequency with the thickness of soil sediments at a particular site. Later on Delgado et al. (2000) has brought up that, correlation between frequency and soil thickness can be directly established even if shear wave velocity remains unknown. Many researchers in the past reviewed the correlations available between depth of bedrock and resonant frequency. Initially, Seth and Wohlenberg (1999) reviewed the relationship between peak frequency and thickness of soil sediment in Germany. Marginal error of less than 15% can be accepted when calculated using the proposed equation (Delgado et al. 2000). In the present study, Eq. (2) has been proposed using nonlinear fitting

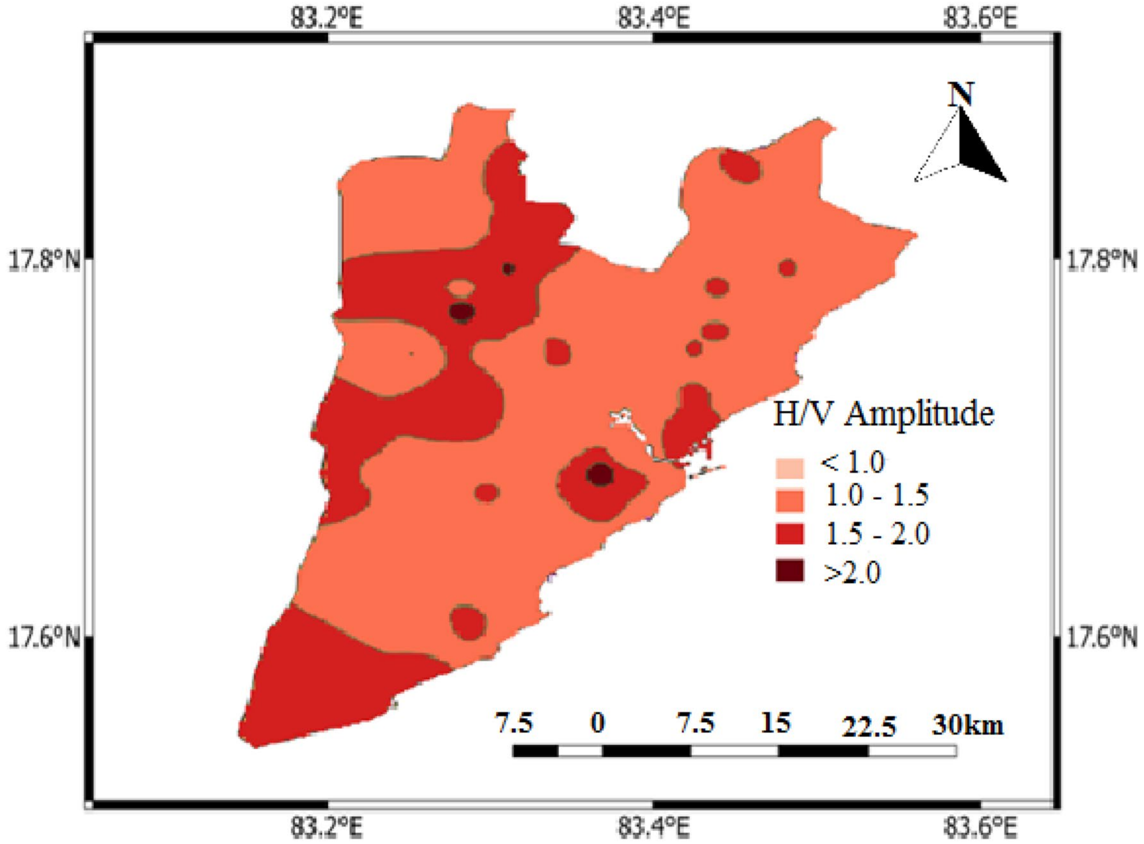


Fig. 8 H/V amplitude map of Vishakhapatnam

between frequency and bedrock depth at the study area, as shown in Fig. 8.

$$y = -2.138x + 24.5578 \left(R^2 = 0.732\right) \quad (2)$$

where "y" is the thickness of soil sediment and "x" is peak resonant frequency. Equation (1) has been used to estimate the thickness of soil sediment using the predominant frequency from microtremor survey. Thickness of soil sediment estimated using proposed equation at various locations has been compared with the actual values from bore logs.

Levenberg–Marquardt algorithm which combines the steepest decent and Gauss's method has been used for nonlinear curve fitting. The fit parameters have been tabulated in Table 3. The curve corresponding to 34 points is as shown in Fig. 10. Parolai et al. (2001) had obtained similar relation for cologne region with parameters a and b as 108.77 and 1.55170.1, respectively. Though the soil properties of the cologne region are different from that of the Vishakhapatnam, the same method can be adopted for estimating a and b values.

4 Conclusions

From the analysis of microtremor recordings, the peak frequency and amplitude have been estimated. The frequency values are ranging from 0.31–10.1 Hz. Figures 7 and 8 are the contour plots representing predominant frequency and

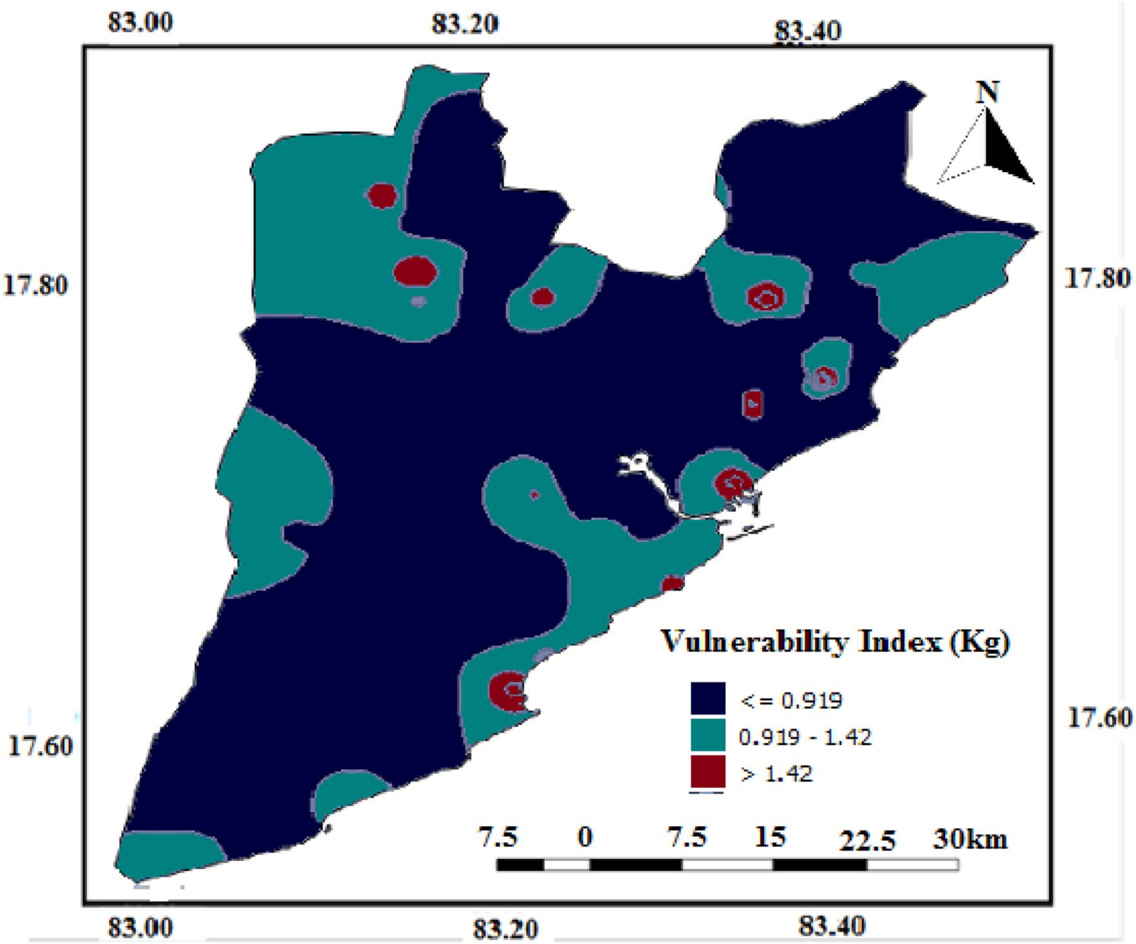


Fig. 9 Vulnerability index map of Vishakhapatnam

H/V amplitude distribution throughout the study area. There is a clear trend in this data for an increase in the resonant frequency from the east (Simhachalam) to the west at Ushodaya junction represents thinning or stiffening of "soft" material overlying a harder "basement" layer. High impedance contrast between the bedrock and sediment has been observed from the distinctive peaks observed in frequency–amplitude plots (plots with peak frequency > 4.0 Hz.) attributing ellipticity of Rayleigh wave. Plots having frequency in the range of 2.0–4.0 Hz. consisted of more than one peak, i.e., secondary peaks existed. This indicates that the source of noise has been distant, i.e., about 50 times the layer thickness. These locations consist of gravel clay and loamy soils. Locations consist of peak frequency and moderate amplitude.

Higher frequency values of (4.0–10.0 Hz) have been observed in many locations in northern and central parts of the study area indicating the presence of rock and gravelly soil with pebbles. These locations with frequency > 4 Hz. were classified as T-I. Some locations in southern and western parts of the study area have shown frequency values of range 2.0–4.0 Hz and were classified as T-II sites. Clayey sand and silty sands are found to be predominant in these locations. Low frequency values of < 2.0 Hz. have been observed at few locations in eastern and central Vishakhapatnam indicating the presence of soft marine clay with higher amplitude values and classified as T-III. The results from the present research will be of great use in infrastructure development. Frequency and H/V amplitude hazard maps are helpful in estimating the critical height of structures that are

Table 3 Comparison of depth of the soil sediments observed from the bore log with depth calculated using the proposed eqn from the study

Location	H/V Frequency (Hz)	Depth of the soil sediment (m)	Depth calculated from proposed eqn. (m)	Difference (%)
L1	9	5.9	6.2	5.08
L2	7	7.0	8.1	15.1
L3	8	6	7.0	16.6
L4	8.8	5.6	6.4	14.3
L5	9.1	6	6.1	1.7
L6	8.5	7.5	6.6	12.0
L7	8.5	8	6.6	17.5
L8	5.8	9	9.9	10.0
L9	7.8	6.5	7.2	10.8
L10	9.6	6	5.8	3.3
L11	9	7	6.2	11.4
L12	9	7.1	6.2	12.7
L13	9	8.3	6.2	25.3
L14	6.9	8.5	8.3	2.4
L15	7.6	9	7.4	17.8
L16	5.4	9.8	10.7	9.2
L17	7.1	9.5	8.0	15.7
L18	3.9	12	15.2	26.7
L19	3.3	13.3	18.2	30.5
L20	4.4	10.5	13.4	27.6
L21	6.2	10	9.3	7.0
L22	4.6	13	12.8	1.5
L23	6	14.5	9.6	33.8
L24	4.2	14.5	14.1	2.6
L25	4.4	16	13.4	16.3
L26	4.7	15.4	12.5	18.8
L27	3.3	16	18.2	13.8
L28	4.6	17	12.8	24.7
L29	3.6	17	16.6	2.4
L30	3.4	19.5	17.6	9.7
L31	2.8	19.5	21.7	11.3
L32	3.8	21	15.7	25.2
L33	2.6	22.5	23.5	4.4
L34	2.9	26	20.9	19.6

proposed in a particular location. Identification of geology and soil characteristics from microtremor survey are helpful in suggesting mitigation measures for soil strengthening.

Vulnerability index (Kg) is observed to be high at Pendurthi, PM Palem and Pothinamallayapalem and northern parts of the city. Some places like MVP colony, Sagarnagar and Kailasagiri have very high vulnerability index because of predominant frequency less than 2.0 Hz and high H/V amplitude, whereas the places like Dwaraka Nagar, Murali nagar, SV colony and Seethammadhara, etc., which are in the north western side have the Kg value ranging from 2.0 to 6.0 and few other locations in the central part of the city have shown very less Kg value (< 2.0) which indicates lesser damage. Vulnerability index from extensive microtremor survey will be useful for estimation and mitigation of hazards and identification of damage prone areas in future.

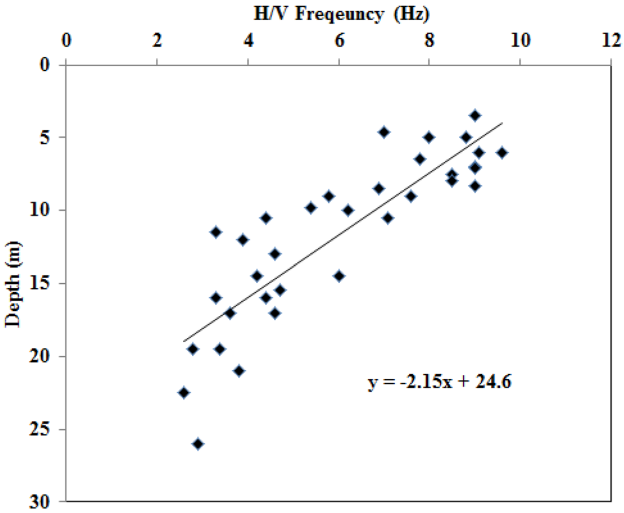


Fig. 10 Plot representing thickness of soil sediment as a function of Peak resonant frequency

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