



Estimation of ground response and local site effects for Vishakhapatnam, India

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Abstract

Ground motion intensity due to an earthquake changes as it disseminates through the soil media from bedrock to the surface. As the ground motion intensity and damage levels mainly depend upon the local site conditions, it is mandatory to carry out the detailed site-specific hazard studies to assure safety of the structure against seismic risk. In this research paper, an effort has been made to estimate seismic hazard associated with the city of Vishakhapatnam. The city lies in east coast region of southern India and falls under seismic zone II (IS 1893-2016 in Criteria for earthquake-resistant design of structures: part 1—general provisions and buildings, Bureau of Indian Standards, New Delhi, 2016). Seismic activity in the Eastern Ghats mobile belt region has increased due to subduction of Burma plate toward the Bay of Bengal, which resulted in activation of inactive faults and new fault development in the region. Therefore, increasing seismic risk and importance of the study area has motivated the researchers to carry out probabilistic seismic hazard assessment and estimation of local site effects using ground response analysis and microtremor testing. From the results, hazard maps were generated in terms of peak ground acceleration (surface, bedrock level), H/V frequency and H/V amplitude. The seismic hazard parameters, uniform hazard response spectrum and hazards curves from probabilistic seismic hazard assessment are further useful in design and construction of prominent structures. The peak ground acceleration at surface and bedrock, predominant frequency and H/V amplitude indicate the variation in local site conditions and will be of great help in seismic design of structures as well as retrofitting of the existing structures to withstand against seismic hazards. Hazard maps from the study will be helpful in further seismic microzonation studies and also identifying zones of potential seismic risk.

Keywords DEEPSOIL · Ground response analysis · Probabilistic seismic hazard · Site effects · Microtremor

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1 Introduction

India has been experiencing numerous earthquakes with varying magnitudes since past. The country is broadly divided into four seismic zones, i.e., Himalayan region, Northeastern region, Gujarat and peninsular India (Raghukanth 2011). The stable central region of peninsular India which was considered to be seismically inactive earlier has experienced earthquakes in the recent past including 1967 Koyna earthquake of magnitude ($M_w = 6.0$), 1969 Bhadrachalam earthquake of magnitude ($M_w = 5.7$), 1993 Latur earthquake of magnitude ($M_w = 6.2$) and 1997 Jabalpur earthquake of magnitude ($M_w = 6.1$). Safety against such earthquakes can be attained with safe seismic design of sub-structure and super-structure. Design engineers are provided with macro-level solutions for geotechnical and geological problems such as hazard maps and earthquake catalogs. From the past literature as well as practical experiences, it was evident that hazard maps and other macro-level solutions provided for a country or a region are not reliable in predicting the exact strong ground motion. This attracted the attention of researchers to carry out site-specific dynamic characterization studies to quantify the local site conditions and seismicity. In the present study, seismic hazard assessment and estimation of local site conditions have been carried out for Vishakhapatnam using geotechnical and seismotectonic data. Rapid infrastructure development with poor construction practices in terms of quality, mushrooming of structures and increased population growth rate also makes the study area more vulnerable for earthquake damage. Increase in seismic activity, the presence of potential faults in the study area, unflattering population growth rate and population density (3800 persons per km^2), industrialization, the presence of two operational ports and importance of the study area financially have motivated the authors to carry out a detailed study.

Probabilistic seismic hazard assessment has been carried out using seismotectonic data (SEISAT 2000) to estimate the hazard parameters associated with regional recurrence. Hazard maps and hazard response spectra have been generated to quantify the seismicity in the study area. Apart from seismic hazard assessment, dynamic site characterization (ground response analysis and microtremor survey) has been carried out using the borehole data collected at several locations throughout the city to estimate the effect of local site conditions. From the results of one-dimensional ground response analysis, it has been observed that many locations at various parts of the study area are prone to higher ground accelerations of 0.14 g. Predominant frequency and amplitude of the soil have been obtained from microtremor survey using HVSR technique (Ohmachi and Nakamura 1992). The peak ground acceleration and predominant frequency hazard maps from the study will cater as an indispensable tool for design engineers and urban planners to analyze and design earthquake-resistant structures in future. Hence, carrying out seismic hazard studies would be of great importance for the study area.

2 Details of the study area

Geological and geotechnical details The port city Vishakhapatnam located in the south-east coast of the country extends between $17^\circ 40' - 17^\circ 45' \text{N}$ latitudes and $83^\circ 10' - 82^\circ 21' \text{E}$ longitudes. The topography of Vishakhapatnam is undulated with hill ranges on three sides (Rao and Neelima Satyam 2007). Major folds are traced in northeast direction and southwest direction of Eastern Ghats hilly region. The city consists of mainly khondalites,

charnockites, quartzites and pegmatites. Topographically, Vishakhapatnam is highly undulated with eroded rock and hills. Visakhapatnam contains meta-sediments, igneous and intrusive igneous rocks which are characteristics of Precambrian age (Rao and Neelima Satyam 2007). Younger formations such as red soils are also present up to a depth of 9 m. Laterites occur as capping to the khondalites and dune sands with black sand concentrations along the beach (Rao 1978).

Around 250 geotechnical boreholes data at 60 different locations across the study area were considered for the analysis, and a minimum of four boreholes have been considered for analysis at each location. From the borehole data, it is evident that the major soil types available in the study area include gravel clay, sandy soil, clay and gravel loams. Red clays are predominant, and gravel clay occupies second place. Red coastal clayey soils consist of low percentage of sand particles (<30%) and mainly fine-grained sizes of silt and clay particles (<0.075 mm). Figure 1a shows the geology map of the study area with available soils. Corrected SPT (N_c) values are observed to be in the range of 5 to >100 throughout the city indicating the presence of rock strata with ($N_c > 100$) and soft sediments of marine clay with ($N_c < 10$). Shear wave velocity values are ranging from as low as 125 m/s to greater than 600 m/s at different locations. Rock outcrops are found at few locations including Seethammadhara, Ayodhya Nagar, Kailasagiri, Durganagar. Ground water table in the city ranges from 3 to 14 m (Subba Rao and Madhusudhana Reddy 2006). The bore holes considered for the analysis are up to a depth of 35 m. Figure 1b shows the locations with available geotechnical bore log data considered for the detailed ground response analysis. The northern and eastern parts of city consist of the water levels (6–12 m) below ground level, whereas western and southern locations consist of water levels above 3 m, i.e., up to 6 m. The lower water table levels in the western locations can be attributed to the flow of Narava Gedda stream.

Seismological details Visakhapatnam city is in intra-plate region and falls under seismic zone II with a zone factor of 0.10 g as shown in Fig. 2. The coast of Vishakhapatnam has been considered to be one of the weaker zones, where neo-tectonic activities were established in the recent past (Jonathan et al. 2012; Putti and Satyam 2018). The seismotectonic data used in the current research within the range of 300 km radius from the site are shown in Fig. 2.

The details of the major seismic events ($\text{MMI} \geq V$) that took place in and around the study area are listed in Table 1. From the earthquake catalog used for seismic hazard assessment, it is evident that all the earthquakes that happened are in the magnitude (M_w) ranging from 2.0 to 6.0. Vishakhapatnam has also experienced the effect of Great Indian ocean tsunami in 2004 ($M_w = 9.3$) to an extent with a tide gauge of 1.4 m height. The worst condition tsunami was found to result in a wave run-up of 4–5 m along the coast of Visakhapatnam (Roshan et al. 2016).

3 Probabilistic seismic hazard analysis (PSHA)

Seismic analysis aims to achieve a performance-based design to ensure whether a structure can withstand certain level of earthquake without undergoing significant damage. The level of strong motion that should be used for any seismic analysis is always a crucial step every design engineer is concerned about. Uncertainties related to the location, size and time should be dealt in order to have accuracy in results. Numerous studies have been conducted throughout the world to quantify the seismic risk posed due to the earthquakes in

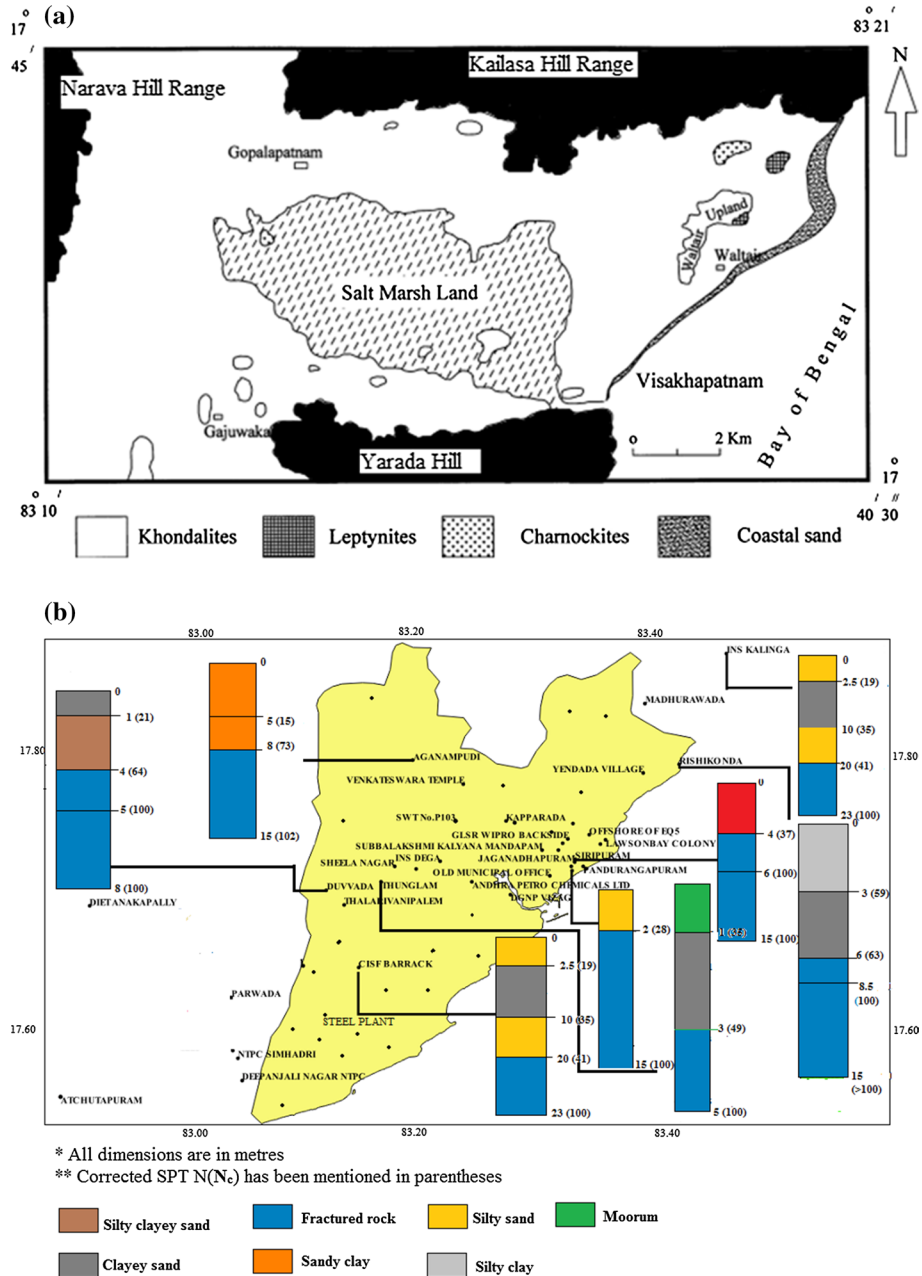


Fig. 1 a Geological map of the study area (Modified from Subba Rao 2008). b Geotechnical bore log data collected

the particular region. Extensive research exists on historical seismic activities and seismic vulnerability at global scale as well as seismic hazard in the locations in and around the Indian subcontinent. Some of the studies include preliminary seismic hazard assessment

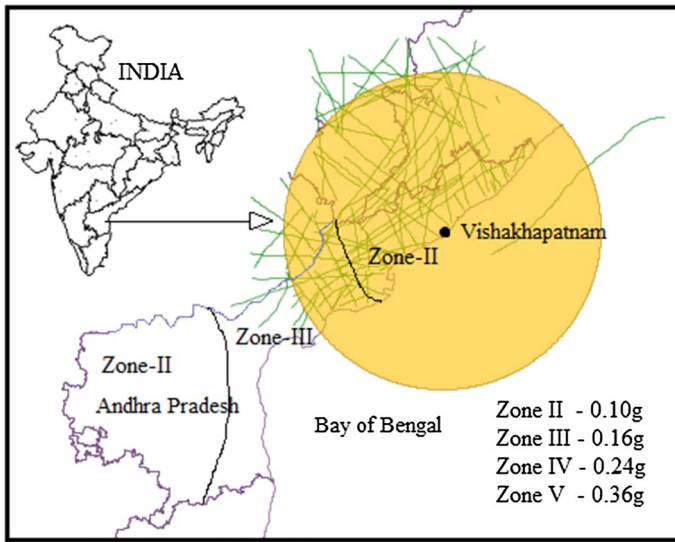


Fig. 2 Location of Vishakhapatnam (India) along with seismotectonic features and seismic zones within 300 km radius (SEISAT 2000)

for important cities including Delhi (Iyengar and Ghosh 2004), Delhi (Rao and Neelima Satyam 2007), Mumbai (Raghukanth and Iyengar 2006), Bangalore (Sitharam and Anbazhagan 2007), Chandigarh (Mundepi 2008), Chennai (Boominathan et al. 2007), Kolkata (Mohanty et al. 2009; Zuccolo et al. 2011) and Peninsular India (Vipin et al. 2009). These studies have established a link between seismic occurrence, cause and associated hazard. PSHA has been carried out in the present study to provide an accurate dissemination of ground motion that can happen at the site. For this purpose, the historic and instrumental seismic data from the years 1828 to 2017 with various magnitudes, collected from USGS, IRIS and other published literature, have been considered. Figure 3 shows the seismicity of the study area with M_w ranging between 2.0 and 6.0 during 1828–2017 (190 years). From the figure, it is evident that there is no record of seismic events between 1838 and 1857 and 1937–1957 and also the seismicity in the study area tends to increase after 1947. For reliable results, data completeness test has been conducted using Stepp's method (1972).

Analyzing the seismotectonic history of the study area helps in better understanding of seismic activity associated with the area. Probabilistic seismic hazard assessment provides a base to establish a design response spectrum by estimating peak ground acceleration and other seismic parameters including spectral acceleration. The detailed methodology adopted for carrying out seismic hazard assessment in the study is shown in Fig. 4.

The first step to carry out in hazard assessment is to analyze the seismic data for its completeness and reliability. Hence, data completeness analysis is carried out using statistical procedure proposed by Stepp (1972) to estimate the reliability of earthquake data considered for the present study. Earthquake data around the site have been collected from various sources between years 1800 and 2017. The threshold magnitude is considered as 3.0. From the data completeness analysis (Fig. 5), it is evident that the data set with magnitudes $M_w > 5.0$ is incomplete. As the data set taken for the present study is incomplete for a particular range of magnitudes, Gutenberg and Richter (1944) recurrence law cannot be

Table 1 List of the seismic events ($M_w > 3.0$) in and around the Vishakhapatnam city. *Source:* ASC-India

S. no.	Earthquake location	Date	Mercalli intensity (MMI)	M_w
1	Ongole-Kanuparti, Andhra Pradesh	18-10-1800	VI	5.0
2	Nellore-Kovur, Andhra Pradesh	31-12-1820	V	4.9
3	Vishakhapatnam, Andhra Pradesh	06-01-1827	V	4.9
4	Srikakulam-Srikurmam, Andhra Pradesh	12-10-1858	V	4.9
5	Guntur-Tenali, Andhra Pradesh	21-07-1859	VI	5.0
6	Guntur-Tenali, Andhra Pradesh	02-08-1859	V	4.9
7	Guntur-Tenali, Andhra Pradesh	09-08-1859	V	4.9
8	Tirupati, Andhra Pradesh	02-02-1860	V	4.9
9	Paruchuru, Andhra Pradesh	11-03-1867	V	4.9
10	Bay of Bengal	01-09-1869	VI	5.0
11	Nellore-Kovur, Andhra Pradesh	02-09-1869	V	4.9
12	Kakinada-Vakalapudi, Andhra Pradesh	19-12-1869	V	4.9
13	Vishakhapatnam, Andhra Pradesh.	19-12-1870	V	4.9
14	Mahadeopur-Sironcha, Andhra Pradesh	22-11-1872	VI	5.0
15	Secunderabad-Hyderabad, Andhra Pradesh	25-10-1876	VI	5.0
16	Bay of Bengal	17-04-1917	VII	6.0
17	Bay of Bengal	19-07-1918	VI	5.0
18	Bhadrachalam, Andhra Pradesh	13-04-1969	VII	6.0
19	Bay of Bengal	08-04-1982	V	4.9
20	Bay of Bengal	01-07-1985	VI	5.0
21	Hyderabad, Andhra Pradesh	16-09-2000	III	3.0
22	Indian ocean	26-12-2004	IX	9.1
23	Narasaraopet, Andhra Pradesh	29-10-2012	III	3.8
24	Konark, Odisha	21-05-2014	VI	6.0
25	Ongole-Prakasam, Andhra Pradesh	25-02-2015	IV	4.6

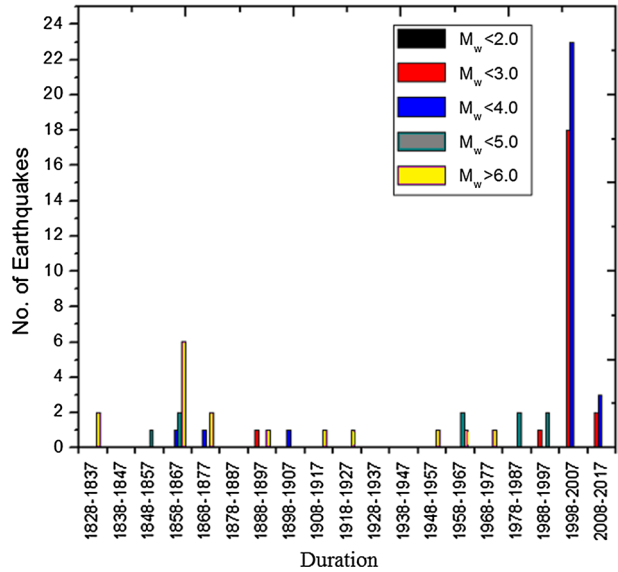
used for the estimation of hazard parameters. Therefore, maximum likelihood method of estimation proposed by Kijko and Sellevoll (1992) has been used in the present study.

Recurrence The regional recurrence model for a particular source indicates the seismic events frequency with respect to magnitude per year. For estimation of the hazard using the instrumental seismic data, distribution of earthquakes frequency with respect to magnitude is estimated using Gutenberg–Richter’s recurrence law (1944) expressed as below

$$\log(N_m) = a - b(M) \quad (1)$$

where M is magnitude of the seismic event, N_m stands for the rate of seismic events with magnitude greater than ‘ M ,’ ‘ a ’ is a real constant which describes the seismic activity, and ‘ b ’ is a tectonic parameter which describes the abundance of larger shocks to smaller shocks relatively. The Gutenberg–Richter law follows a truncated exponential distribution in estimation of maximum magnitude M_w , whereas Kijko–Sellevoll method is free from the instinctive judgment involved in identifying seismogenic sources. When specific active faults have not been mapped and the causes of seismicity are not fully understood, Kijko–Sellevoll technique takes the incompleteness and errors in earthquake

Fig. 3 Seismic history of the study area



catalog into account. Using Kijko–Sellevoll maximum likelihood approach, a and b parameters obtained are 2.403 and 0.691, respectively. Maximum likelihood approach has been adopted due to availability of incomplete seismic data for the study area. The regional recurrence relationship is shown in Fig. 6.

It has been observed that the values of seismic hazard parameters a and b obtained are comparable with the values from the past research carried out for peninsular India and southern India. Many researchers established region-specific hazard parameters. The results that define the regional recurrence from the current study match well with past studies in peninsular India. Sitharam and Anbazhagan (2007) have conducted seismic hazard studies for Bangalore which is in zone II (IS 1893-2016, 2016) and suggested the value of parameter b value to be from 0.62 to 0.98; Jaiswal and Sinha (2007) have suggested value of b is 0.88 ± 0.7 ; and according to Ram and Rathore (1970) the values are $a = 4.58$ and $b = 0.891$. Kaila et al. (1972) also suggested b value of 0.7 for peninsular India.

The probability density function which is a function of hypo-central or epicentral distance is assumed to be distributed evenly along the length of the fault. In this study, nearest fault F4 with higher magnitude has been considered to plot probability density function (PDF) and cumulative distribution function (CDF). Figure 7a, b shows typical plots of probability density function and cumulative distribution function by considering the nearest line source (fault F4) to the site.

Ground motion prediction model Around 103 seismic sources are identified which include faults, lineaments, shear zones and ridges within 300 km radius. Five potential sources with higher magnitude ($M_w > 5.0$) have been considered in this study for the detailed hazard analysis. The list of seismic sources considered for the detailed hazard assessment is given in Table 2.

Researchers have developed diverse attenuation relationships since past, to estimate spectral acceleration (S_a/g) and PGA. The ground motion prediction model (GMPM) shows the change of PGA with respect to vibration periods and damping ratios for a particular magnitude (M_w) and distance (R). In this study, hazard curves have been generated

Fig. 4 Procedure for seismic hazard assessment

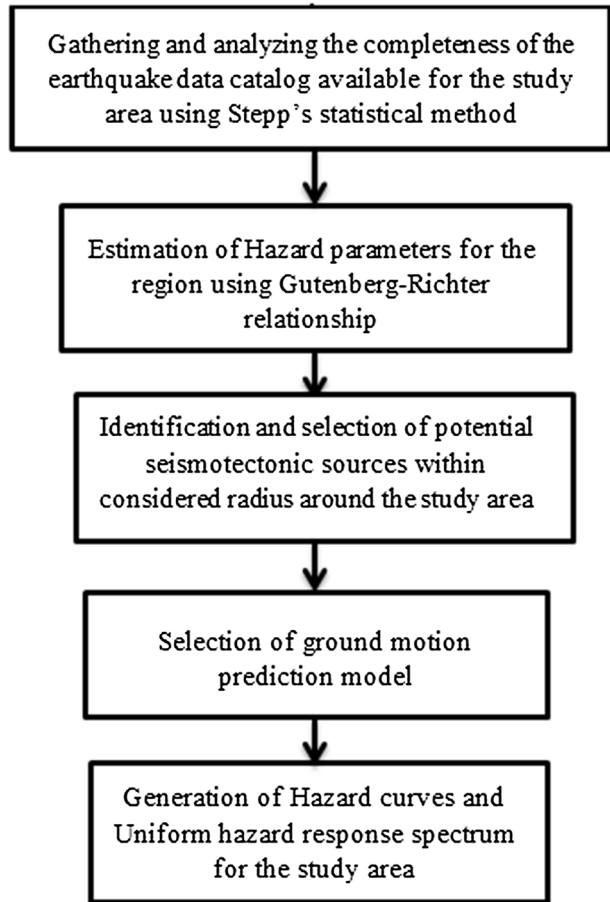


Fig. 5 Analysis of data completeness using Stepp's method (1972)

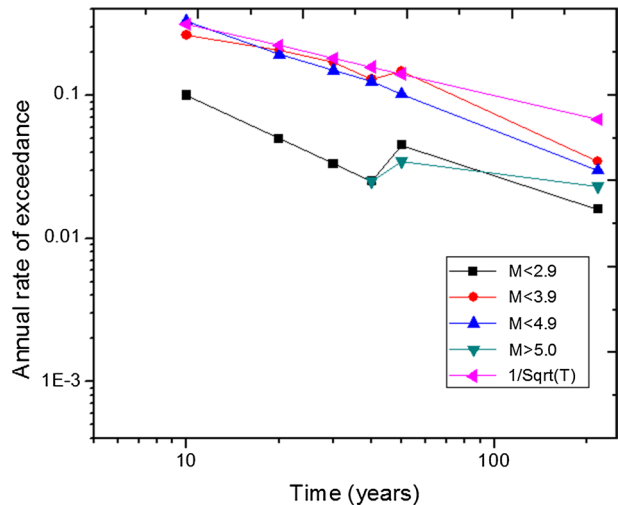


Fig. 6 Frequency–magnitude distribution plot using Kijko–Sellevoll method (1992)

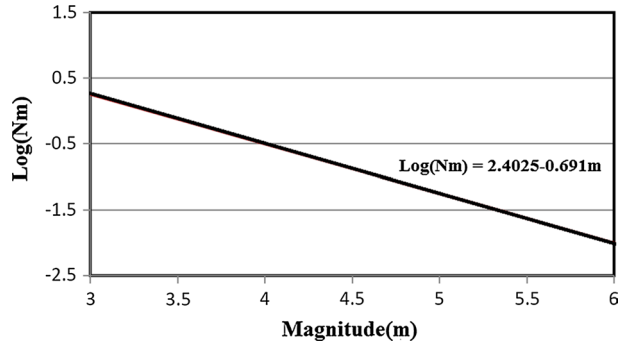


Fig. 7 a PDF versus magnitude (M_w) and **b** CDF versus magnitude (M_w)

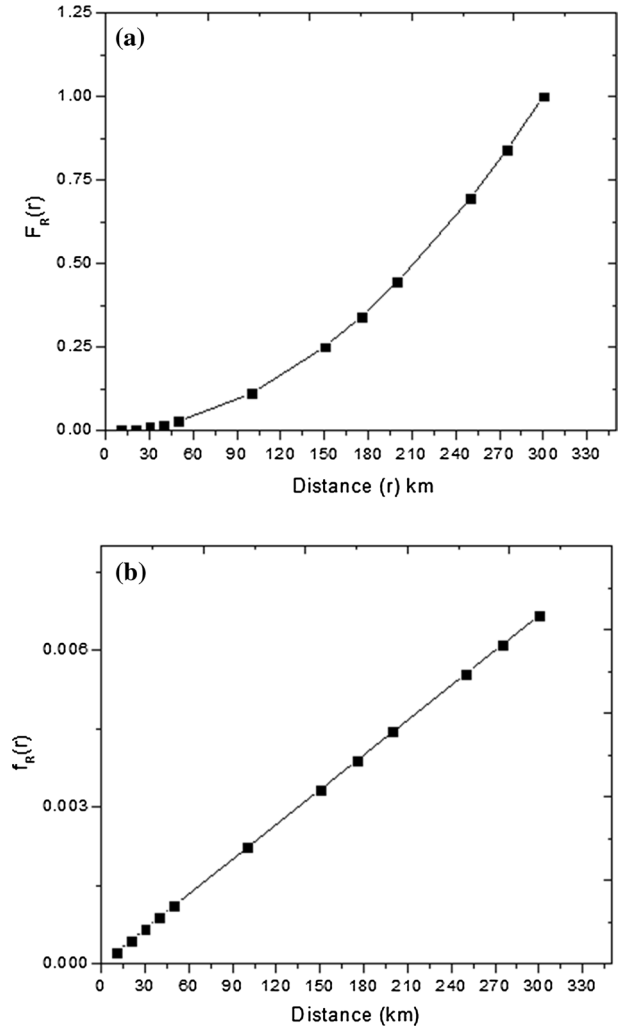
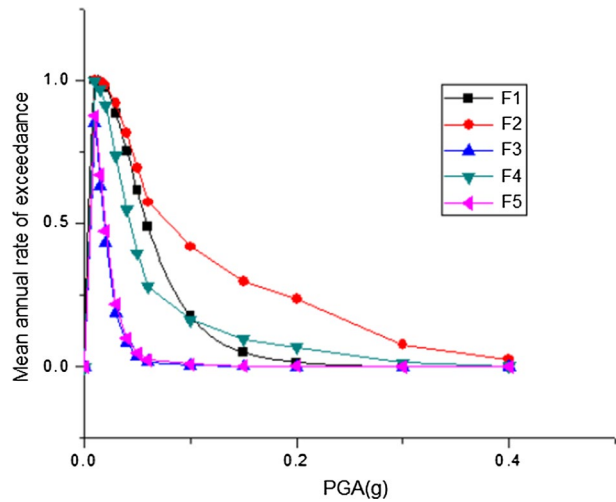


Table 2 Seismic sources considered

Sources considered	Latitude	Longitude	Magnitude (M_w)	Fault length (km)	Distance from site (km)
F1	83.864	20.780	6.0	52	154
F2	83.245	17.837	6.0	47	121
F3	83.099	17.613	6.0	123	88
F4	83.939	18.699	5.0	32	76
F5	82.587	20.959	5.0	64	152

Fig. 8 Hazard curves for potential sources at bedrock level



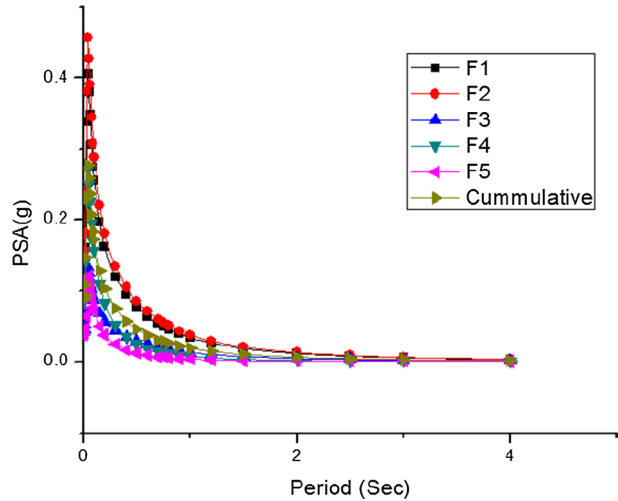
for the five potential faults at bed rock level (Fig. 8). Hazard curves with exceedance probability of 0.1 in 50 years for 475 years of return period have been calculated. The attenuation relationship given by Raghukanth and Iyengar (2006) for peninsular India has been considered in the present study for hazard curve generation.

$$\ln(Y_{br}) = C1 + C2(M - 6) + C3(M - 6)^2 - \ln(R) - C4R + \ln(\epsilon_{br}) \tag{2}$$

where Y_{br} is spectral acceleration (Sa/g) or PGA, M_w is the moment magnitude, whereas R and ϵ_{br} refer to hypo-central distance and error in regression. C_1 , C_2 , C_3 and C_4 are the site-specific constants (Raghukanth and Iyengar 2006) for peninsular India.

Uniform hazard response spectrum is a response spectrum with equal probability of exceedance at all structural periods for a particular hazard. It has been derived from a probabilistic analysis that has uniform probability of being exceeded at each vibration period. This can be performed by developing hazard curves for various periods to define the response spectrum. Thereafter, for a specified return period of exceedance probability, the ordinates are picked from hazard curves for each spectral acceleration and an equivalent hazard response spectrum has been generated. Figure 9 shows the response spectrum with 5% damping ratio at bed rock level. The shape of the response spectrum attained from the present study matches with the one of Mumbai city developed by Raghukanth and Iyengar (2006). The spectral acceleration at zero period is observed to be 0.11 g from the present

Fig. 9 Uniform hazard response spectra (UHRS)



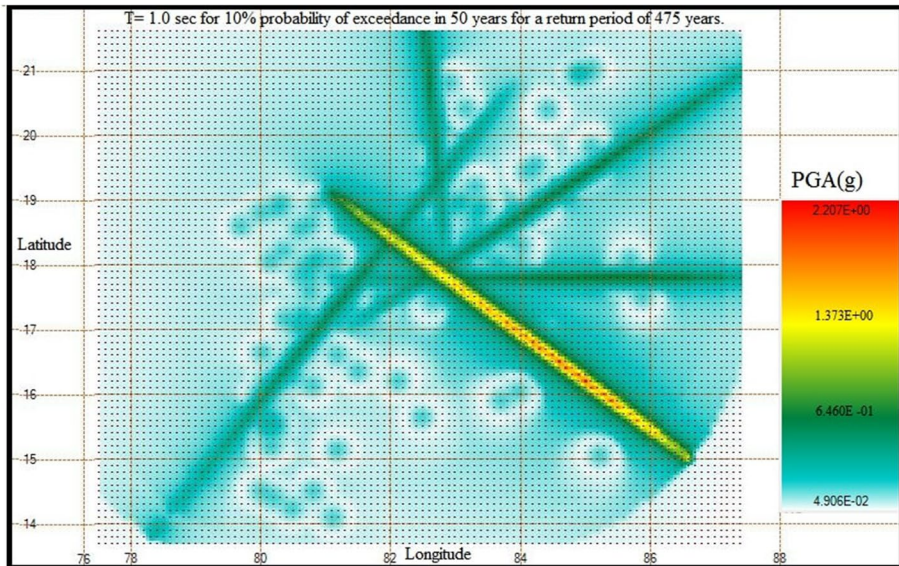
study. Apart from the hazard curves and response spectra, hazard maps have been prepared for the study area which will be very helpful in identifying potential seismic risk associated with the study area. The hazard maps have been generated considering five major faults and 132 point sources within 300 km radius from the site for a structural period of $T=1.0$ s and 2.0 s and exceedance probability of 0.1 in 50 years for 475 years of return period. The locations with higher intensity in the hazard map (sharp yellow bars and several green lined zones) are due to the presence of faults (F1–F5) beneath the surface. From the hazard maps, higher response has been observed along the fault F4 and its nearest locations. Most of the locations in eastern part of the study area along the coast line have shown higher response compared to other parts. Faults Kanada kumali (F1) and Vamsadhara (F2) and Nagavali (F4) have their impact on the hazard associated with the study area compared to other faults and seismotectonic sources. Figure 10a, b shows the variation of peak ground acceleration throughout the study area at a time period of 0.1 s and 0.2 s with an exceedance probability of 0.1 in 50 years for a return period of 475 years, respectively.

The probabilistic hazard curves developed are further useful in design of prominent structures in the study area. The results from PSHA have been compared and are observed to be in good match with the seismic hazard parameters provided by National Disaster Management Authority (NDMA 2012). The PGA value was found to be 0.1 g for exceedance probability of 0.1 in 50 years at bedrock level and found to be having a reliable match with the results of seismic hazard assessment of Bangalore city (Sitharam and Anbazhagan 2007) which is in southern peninsular India.

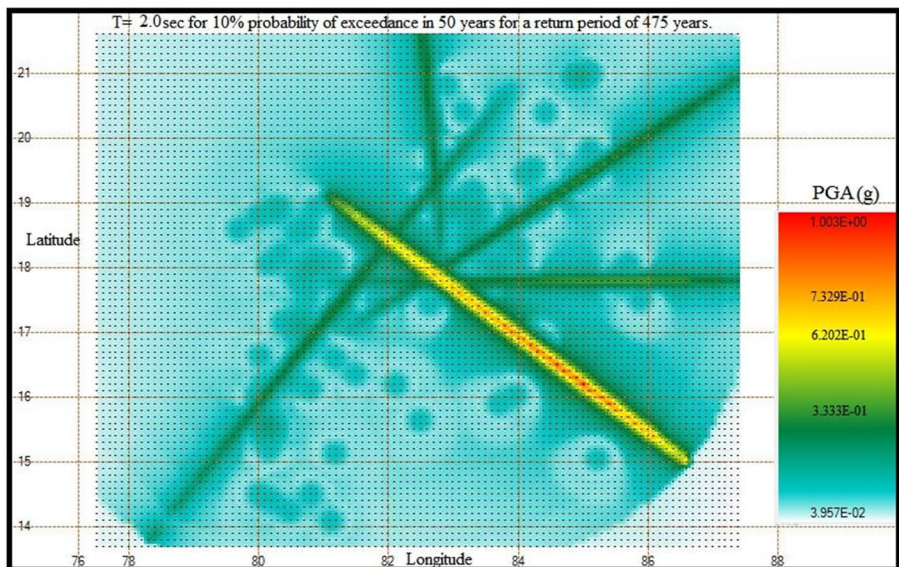
Apart from probabilistic seismic hazard assessment, ground response analysis has been carried out which is useful for the prediction of local site effects and to estimate the dynamic behavior of the soil during seismic loading.

4 Ground response analysis (GRA)

The seismic damage level of a structure depends upon the response of soil to the seismic waves propagated through the soil during an earthquake. Site effects along with ground response play a prominent role in estimation of behavior of soils under earthquake loading.



(a) T= 1.0 sec



(b) T=2.0 sec

Fig. 10 Probabilistic hazard map of Visakhapatnam with an exceedance probability of 0.1 in 50 years for 475 years of return period

Therefore, dynamic site characterization has been carried out through GRA to understand seismic risk associated with the study area.

One-dimensional GRA has been carried out through equivalent linear approach to estimate the behavior of soil under the influence of strong motion. Theoretical approaches require conducting different sensitivity tests based on the requirement for different

locations, and analyzing uncertainty is highly impractical (Manne and Satyam 2011). 1-D wave propagation method is extensively used method for GRA due to its availability, simplicity and obstinate results (Schnabel et al. 1972). 1-D response analysis deals with propagation of shear waves through a linear viscoelastic system in vertical direction. For representation of viscoelastic wave propagation, soil behavior is modeled as Kelvin–Voigt solid where the material resistance to shearing deformation is the sum of viscous and elastic parts) with viscous damping along with linear elastic shear modulus. The solution for one-dimensional equation of motion of shear waves (SH) propagating in Z direction yields site response. Equivalent linear GRA has been carried out where the site is assumed to be horizontally layered and single value of damping and stiffness are used for all components of frequency using DEEPSOIL (Youssef 2009). Shear modulus (G/G_{\max}) and damping ratio (ζ) are defined as functions of strain. DEEPSOIL includes the modified hyperbolic model developed by Matasovic and Vucetic (1993) adding the parameters ' β ' and ' s ' which are given for backbone curve shape adjustment and represented as

$$\tau = \frac{G_{\text{mo}}}{1 + \beta\{\gamma|\gamma_r\}^s} \quad (3)$$

where G_{mo} is shear modulus; s is the shear strength, and γ is shear strain of the soil. γ_r is the reference shear strain, evaluated using reference shear stress and initial shear modulus. The procedure for ground response analysis includes defining soil, rock properties and soil model followed by analysis control and input ground motion.

For detailed GRA, 60 locations with 250 boreholes at 60 different locations were considered and the input parameters given are strong ground motion parameters and dynamic properties of the soil. 2001 Bhuj earthquake ($M_w=7.7$) strong motion data have been considered with a maximum horizontal acceleration of 0.106 g and bracketed duration of 19.98 s. Equivalent linear approach uses frequency domain analysis to get a solution and is computationally effective. But it is always an approximation of nonlinear cyclic behavior of soils (Hashash et al. 2012). In the study area, disintegrated rock has been found at a depth of 30–35 m in many locations and rock outcrops have been identified at few locations. In this study, depth of bedrock is assumed to be below the last layer, and to prevent erroneous results, the last layer was assumed to be the same up to a depth of 100 m. PGA values at surface and that at bedrock were computed from the analysis. The surface PGA values are estimated to be in the range of 0.08–0.14 g. Amplification factor which is a ratio of PGA at surface to that of the acceleration at bed rock is often used as prominent parameters for estimation of ground response. Peak spectral amplification factor (PSA) (Fig. 11) varies from 1.0 to 1.5. The spectral acceleration value has increased with increase in water table, and the ground motion is found to be amplified predominantly at the surface.

PGA values were used to characterize the study area into different zones. PGA maps at surface and bedrock level have been generated for the study area as shown in Fig. 12a, b. Based on the values of PGA, the city is divided into three major zones. It has been observed that many locations have PGA on higher side up to 0.14 g. The locations with ground water table at greater depths, i.e., Kothapalem, Tikkavanipalem, Muralinagar, Bapujinagar, etc., have shown greater response compared to the locations with water table at shallow depths. These locations have been characterized with soft disintegrated rock, gravelly sand with pebbles, sandy gravels and stiff clays as predominant soils. Sagarnagar, Rushikonda and few areas near the port which are located along the coast line have shown PGA values less than 0.10 g where silty sand, sand and clayey sand are found to be predominant.

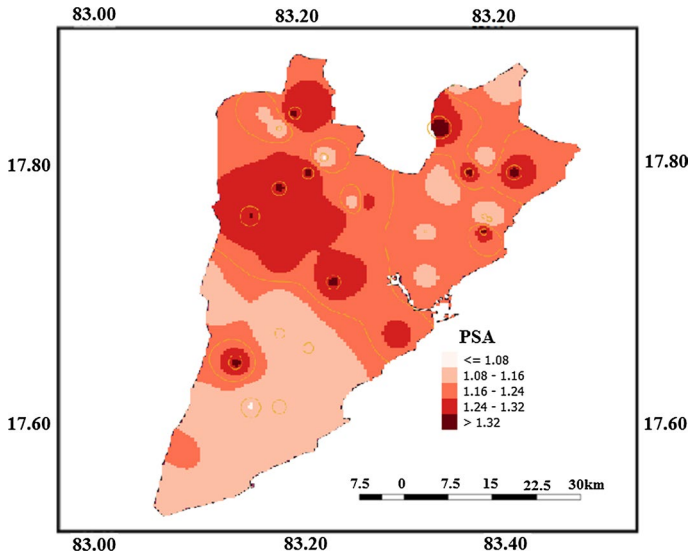


Fig. 11 Peak spectral acceleration map

Site effects along with ground response analysis play a prominent role in estimation of behavior of soils under earthquake loading. Therefore, local site effects were estimated using microtremor survey to have a clear picture of seismic risk associated with the study area.

5 Local site effects

Extensive research has been carried out (Nakamura 2000; Gosar 2007; Herak et al. 2009) to correlate the intensity of damage with surface geology properties estimated from ambient noise vibrations. Usually, site effects are represented in the form of frequency and amplitude. Predominant frequency represents the maximum amplitude of the ground motion in frequency domain. Findings of the site amplification and site effects provide a platform for seismic hazard mitigation process, as different soils responds differently when it is subjected to ground motion. If the predominant frequency of the soil layers and natural frequency of the buildings are close, higher vulnerability of the building can be predicted owing to resonance effects. Microtremors have gained priority in assessment of dynamic properties of soils such as frequency and amplitude (Neelima Satyam and Towhata 2016). Microtremor survey with multiple sensors can be used for the estimation of shear wave velocity and sediment thickness. Kuo et al. (2009) compared three different methods for evaluation of shear wave velocity and evidenced that microtremor is efficient in estimation of the values. In the present research, microtremor survey has been employed to estimate the local site effects using horizontal-to-vertical spectral ratio (HVSr) method. The reliability of HVSr method has been scrutinized by many researchers by matching the results with the analysis from strong motion records (Chavez-Garcia and Cuenca 1996; Teves-Costa et al. 1995; Bour et al. 1998; Jensen 2000; Chavez-Garcia and Tejeda 2010; Surve and Mohan 2010). The most intricate steps in practicing microtremor to estimate dynamic

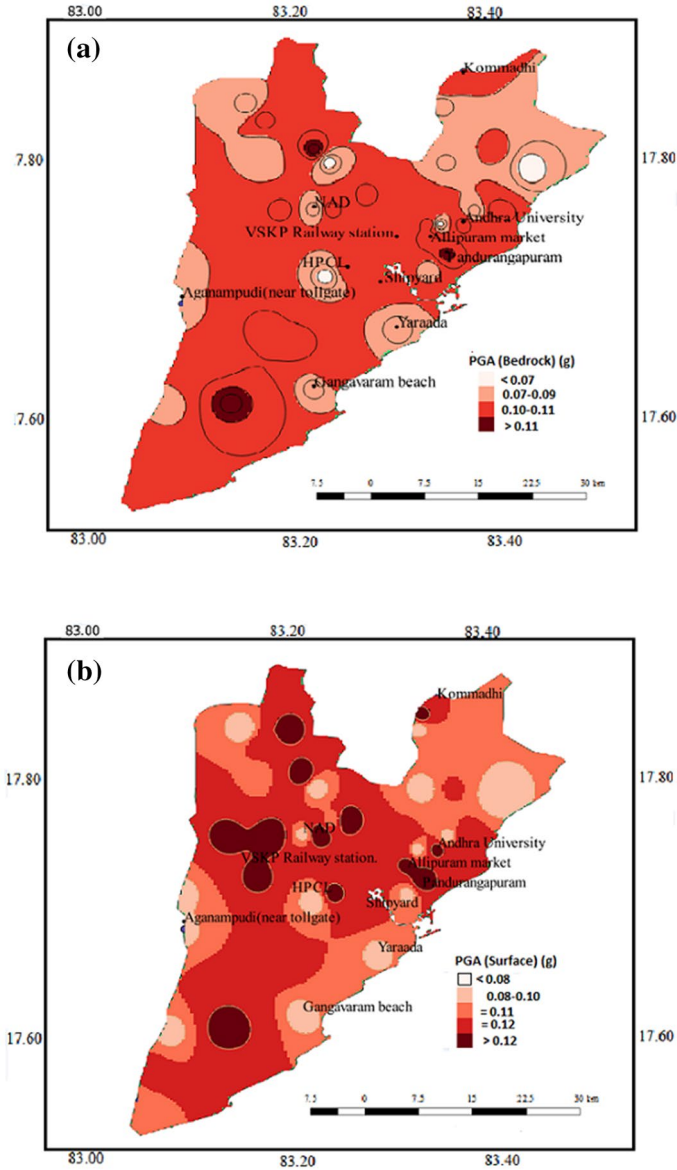


Fig. 12 **a** Peak ground acceleration (g) map at bed rock and **b** peak ground acceleration (g) map at surface

properties are data acquisition, data processing and analysis. Abundant information regarding the recorded site and source of noise is available from the type and form of the H/V peaks.

The peaks within the range of frequency 0–10 Hz were only considered for the analysis sites, and a classification is also proposed based on shape of the curve, soil characteristics, predominant frequency and H/V amplitude. The sensor (Fig. 13) has to be leveled on the ground to prevent baseline error, and ambient noise has been recorded for duration of

Fig. 13 Instrument set up at a test site (Arilova)

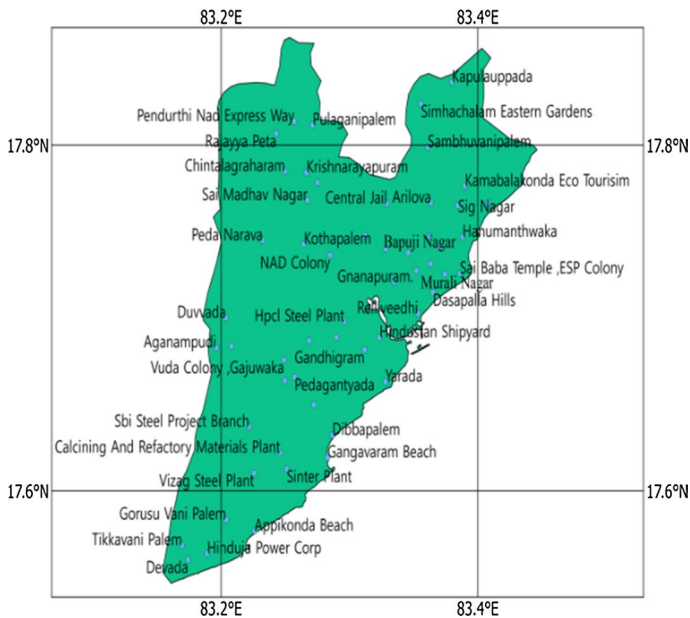


Fig. 14 Microtremor test locations in the study area

60 min with 1 s pre-event and post-event time. Microtremor test has been conducted at 75 locations (Fig. 14) scattering all over the city. Two horizontal and one vertical components, i.e., three components of movement, were recorded at each location stretching from Anakapalli to Bheemunipatnam for HVSR analysis. From the analysis, predominant frequency and the corresponding H/V amplitude were estimated at the test location.

Based on the frequency values, soil type, corrected SPT (N_c) values, shear wave velocity and response spectrum plot trend, site characterization was done classifying the study area into three major zones of types I, II and III. Table 3 gives the details of predominant frequency and H/V amplitude at all the test locations.

Table 3 H/V frequency and amplitude for all test locations

S. no.	Location	Latitude	Longitude	H/V frequency (Hz)	H/V amplitude	Classification
1	Tikkavanipalem	17.57	83.12	4.6	1.7	I
2	Au south campus	17.73	83.32	6.5	1.2	I
3	Bapujinagar	17.74	83.28	4.2	1.2	I
4	Bullayya college	17.73	83.31	5.7	1.4	I
5	Near calcining plant	17.62	83.20	4.2	1.1	I
6	Central jail	17.77	83.28	4.5	1.2	I
7	Chintalagraharam	17.78	83.20	4.5	1.3	I
8	Daba gardens	17.72	83.30	5.1	1.8	I
9	Dasapalla Hills	17.71	83.31	6.7	1.5	I
10	Gandhigram	17.68	83.26	4.8	2.4	I
11	Gnanapuram	17.72	83.28	4.9	1.1	I
12	Near shipyard	17.69	83.27	4.9	1.2	I
13	HPCL steel plant	17.70	83.25	5.1	1.4	I
14	Kothapalem	17.74	83.21	9.0	1.5	I
15	Krishnarayapuram	17.78	83.22	8.3	2.1	I
16	Kshatriya kalyanamandapam	17.75	83.31	7.1	1.8	I
17	Muralinagar colony	17.75	83.26	9.8	1.4	I
18	Nattayapalem	17.71	83.20	6.8	1.9	I
19	VS Krishna govt college	17.74	83.32	6.8	1.2	I
20	NT college road	17.74	83.30	7.6	1.6	I
21	Padmanabhanagar	17.76	83.2	5.8	2.6	I
22	Pedaranava	17.74	83.18	5.6	1.1	I
23	Durganagar	17.739	83.18	6.1	1.6	I
24	Near Pendurthi-Nad Exp.way	17.81	83.21	4.1	1.4	I
25	Pulaganipalem	17.81	83.22	7.2	1.9	I
26	ESP colony	17.73	83.34	6.6	1.1	I
27	Saimadhavnagar	17.77	83.22	6.2	2.1	I
28	Sambhuvanipalem	17.80	83.31	5.6	1.1	I
29	Near SBI steel project	17.64	83.17	7.6	1.5	I
30	Shanthinagar	17.74	83.24	8.7	1.7	I
31	Sig nagar	17.77	83.33	5.3	1.3	I
32	Simhachalam eastern gardens	17.82	83.31	7.2	1.3	I
33	Simhapuri colony	17.78	83.23	8.6	1.8	I
34	Sinter plant	17.61	83.20	4.1	1.9	I
35	Steel Mont pvt	17.65	83.22	4.5	1.2	I
36	Vizag steel plant	17.61	83.18	7.8	1.3	I
37	Adarshnagar road	17.74	83.34	5.3	1.3	I
38	Appikonda beach	17.58	83.18	2.3	1.7	II
39	Chinnapalem	17.61	83.13	2.4	1.5	II
40	Kalinganagar	17.75	83.25	2.5	1.2	II
41	Kamabalakonda eco tourism	17.78	83.34	2.3	1.6	II
42	Devada	17.56	83.12	2.2	1.7	II
43	Dibbapalem	17.63	83.24	2.3	1.4	II

Table 3 (continued)

S. no.	Location	Latitude	Longitude	H/V frequency (Hz)	H/V amplitude	Classification
44	Godduvanipalem	17.66	83.20	2.4	1.3	II
45	Gorusuvanipalem	17.58	83.15	2.8	1.7	II
46	Dondaparthi area	17.73	83.30	3.2	1.2	II
47	Kommadi	17.83	83.32	3.1	1.7	II
48	Mudasarlova park	17.76	83.31	3.8	1.3	II
49	Narasimhanagar	17.74	83.30	2.1	1.5	II
50	Pedagantyada	17.67	83.21	2.6	1.7	II
51	Vuda colony, Gajuwaka	17.68	83.20	3.5	1.2	II
52	Pedamadaka	17.65	83.22	3.2	1.3	II
53	Pendurti	17.80	83.21	2.1	1.1	II
54	Shivajinagar road	17.68	83.16	2.3	1.4	II
55	Siddeswaram	17.61	83.19	3.0	1.1	II
56	MVP colony	17.738	83.34	2.7	1.3	II
57	Near Airport	17.76	83.32	2.3	1.2	II
58	Rajayyapeta	17.81	83.19	0.5	1.2	III
59	Relliveedhi	17.70	83.30	1.1	1.9	III
60	Aganampudi	17.68	83.15	1.8	1.8	III
61	Arilova	17.77	83.31	0.7	1.6	III
62	Duvvada	17.70	83.15	1.2	1.6	III
63	Gangavaram beach	17.62	83.23	0.5	1.3	III
64	Kapuluppada	17.84	83.33	1.9	1.4	III
65	NAD colony	17.74	83.23	1.9	1.2	III
66	Near NTR centre	17.77	83.36	0.9	1.6	III
67	Yarada	17.66	83.28	0.9	1.4	III
68	Sriharipuram	17.69	83.24	0.7	1.2	III
69	Porlupalem	17.77	83.20	1.4	1.1	III
70	Seshadri nagar colony	17.78	83.20	0.8	2.1	III
71	Gidijala	17.89	83.29	0.6	1.4	III
72	Dwaraka Nagar	17.73	83.31	0.7	1.2	III
73	Srinivas Nagar	17.77	83.24	0.5	1.1	III
74	Isukathota	17.74	83.33	0.4	1.5	III
75	Sagarnagar	17.76	83.36	0.9	1.1	III

It was observed from the microtremor results that many locations in the northern part of the city such as Tikkavanipalem, Bullayya college, Dasapalla hills and Kothapalem have shown higher frequency values indicating the presence of gravelly soil with pebbles, weathered rock and the presence of rock in few places with a thin layer of soil cover. In these places, the frequency values are as high as 10 Hz resulting in lower amplification values. These locations with frequency > 4 Hz. were classified as type I. Some locations in southern part of the city and western part of the city, i.e., MVP colony, Siddeswaram, Pedagantyada, Vuda colony, etc., have shown frequency values of range 2.0–4.0 Hz and were classified as type II sites. These locations has

silty sand and clayey sand as predominant soils. Other locations in eastern part of the city and few locations in the central part were classified as type III (Dwaraka Nagar, Srinivas Nagar, NTR centre, Seshadri nagar colony, etc.) and have shown frequency values < 2.0 Hz indicating the presence of soft clay and marine clay with higher amplitude values. Figure 15 shows typical response spectra at some test locations classified as types I, II and III, respectively. Table 4 shows the classification proposed in the present research based on predominant frequency and H/V amplitude values from microtremor testing.

Predominant frequency values from the frequency–amplitude spectra at various locations have been used to generate a hazard map to the study area. Potential risk zones and local geology conditions in the study area can be identified from the hazard map (Fig. 16). Potential danger of soil structure resonance can be detected using the predominant frequency map while designing the structure against seismic hazard in a particular location. It provides a fundamental base for site response analysis, particularly in urban areas (densely populated) where conventional seismic techniques cannot be utilized.

6 Conclusions

After the devastating experience of 2001 Bhuj earthquake ($M_w=7.7$), no region in India is considered to be safe against seismic hazards (NDMA 2008). It is noteworthy that though the earthquakes in peninsular region are of magnitude less than 7.0, the casualties and damages are very large indicating poor construction practices and lack of awareness. Hence, it is suggested to carryout hazard assessment and site characterization studies in the present study area Vishakhapatnam as it is a prominent port city with well-established industries in the state of Andhra Pradesh (India).

PSHA has been carried out to estimate the hazard associated with the city. Seismic hazard parameters from the analysis were estimated to be $a=2.403$ and $b=0.691$ using maximum likelihood method. These seismic hazard parameters define the regional recurrence. The spectral acceleration is found to be 0.11 g from the present study. Findings from PSHA were found to be in good agreement with values provided in the past literature for the peninsular region (India). Hazard maps can be utilized to spot the locations with higher seismic risk.

From ground response analysis, it has been identified that the values of PGA at surface are high at places with higher water table depth along with the presence of sand, silt. It was observed that depth of water table from ground surface has significant influence on all ground response parameters. PGA values at surface level range from 0.08 to 0.14 g, whereas the PGA at bedrock level varies in a range of 0.08–0.12 g.

Predominant frequency and H/V amplitude estimated from microtremor testing can be further used to develop an iso-frequency map for the city. The frequency values are ranging from 0.44 to 10.1 Hz. The H/V plots of the locations Muralinagar, Pedanarava, Gnana-puram, Dabagardens, etc., with frequency value greater than 4 Hz (type I) have shown a clear distinctive peak indicating high impedance contrast between the bed rock and the soil sediment, whereas plots for the locations with frequency range of 2.0–4.0 Hz (type II), i.e., Dondaparathi, Kommadi, Pendurthi, etc., have shown two peaks. It was observed that the areas with gravely sand and soft disintegrated rock have shown higher frequency values > 4.0 Hz and locations with soft clay deposits and marine clay deposit, i.e., few areas

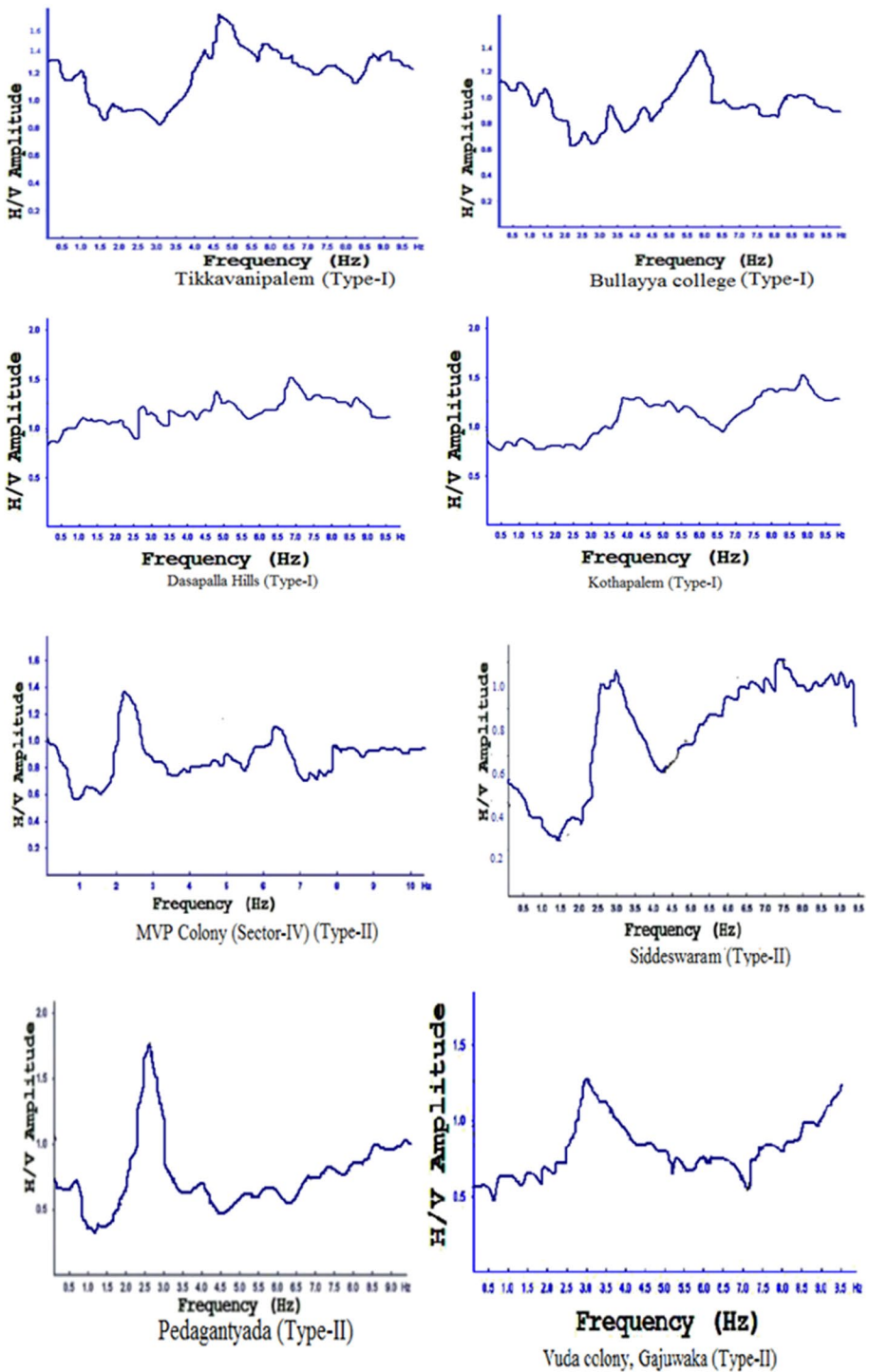


Fig. 15 H/V amplitude spectra considered for site classification

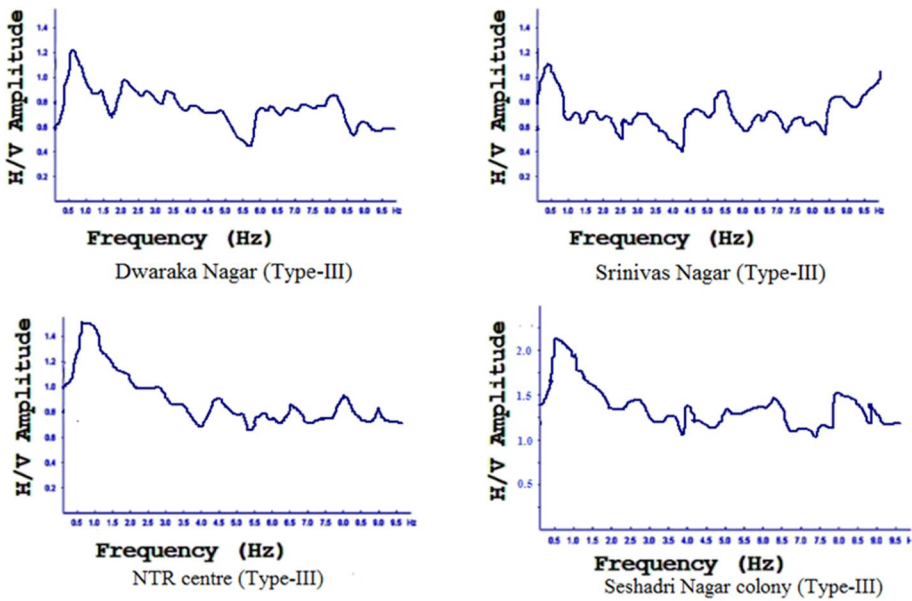


Fig. 15 (continued)

Table 4 Site classification based on microtremor results

S. no.	Proposed class	Fundamental frequency (Hz)	Type of soil	N_c	V_s (m/s)
1	Type I	> 4.0 Hz	Gravelly sand, gravel with pebbles, soft disintegrated rock	> 40	> 310
2	Type II	2.0–4.0 Hz	Silty sand, clayey sand, sandy silts, red moorum	15–40	220–310
3	Type III	< 2.0 Hz	Soft clays, marine clays, silty clay	< 15	< 220

near to port and coast line, have shown lower frequency values of less than 2.0 Hz (type III). Lower predominant frequency values of the soil refer to topography changes which cannot be accounted in theoretical ground response analysis. It is well known that soft soil deposits with low-frequency range amplify the ground motion resulting in higher acceleration values. In contrast, from the comparison of results from GRA and microtremor it has been observed that higher acceleration values were attained at areas with stiffer soils where the seismic wave gets attenuated.

The results will be very helpful in further development of infrastructure in the city. Peak ground acceleration values can be picked from surface PGA maps developed in the present research for earthquake-resistant analysis and design of structures. Iso-frequency maps will be useful in deciding the critical height of structures that can be built in a particular location. These findings can be further used in planning, development and management of the upcoming industries, ports and other infrastructures. Implementation and usage of these results in practice results in reduced seismic risk and damage from future earthquakes.

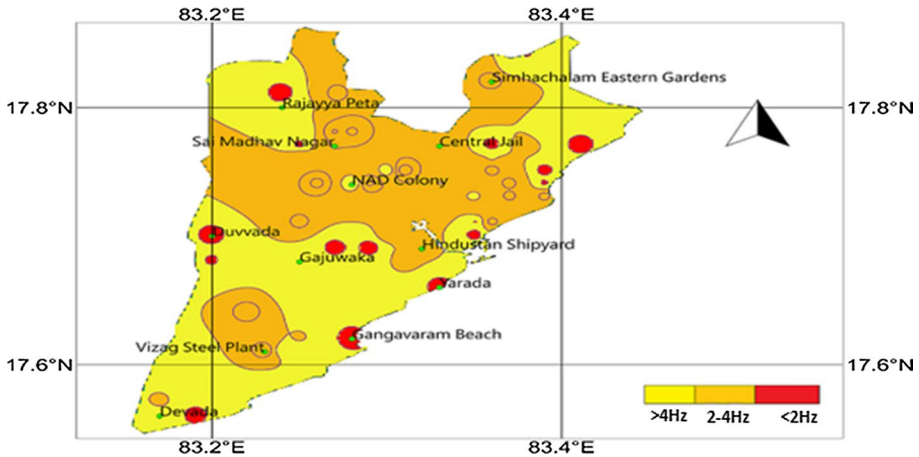


Fig. 16 Predominant frequency map of the study area

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