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Site-specific ground response analysis and liquefaction assessment of Vijayawada city (India)

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Abstract Safety against earthquake hazards can be achieved by considering site safety against geotechnical problems and structural safety against dynamic forces. Geotechnical problems such as amplification, landsliding and soil liquefaction are dangerous in regard to the scale of damage. Assessment of risk against such problems is a part of seismic microzonation process. Seismic risk is highly affected by risk factors due to geological environment and geotechnical properties of soils. In this study, it is attempted to identify and develop hazard maps against seismic hazard for Vijayawada city, India, where the subsoil consists of thick alluvial formations along the river. In particular, the study aims at the evaluation of site effects using the available geotechnical data and carrying out microtremor testing in the study area. The geotechnical zonation of the subsoil of the city suggests a high vulnerability of the physical environment in addition to site amplification of the ground motion phenomena. The ground response analysis at the surface was conducted by 1D equivalent linear method and by microtremor testing. From the ground response analysis, peak acceleration, frequency and amplification parameters were assessed and the city was divided into different zones corresponding to each value. Liquefaction hazard was quantified using SPT-based method in combination with the dynamic analysis. These findings supply an indispensible tool for the seismic retrofitting of the buildings and for the mitigation of the seismic risk for small to medium earthquakes in the city.

Keywords Site characterization · Seismic ground response · Microtremor · Liquefaction

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1 Introduction

Prevention of seismic hazard is extremely difficult but evaluation of seismic risk facilitates preparedness during emergency. Seismic risk has been swiftly increasing in India. Earthquakes in the last two decades (1988 Bihar–Nepal; 1991 Uttarkashi; 1993 Latur; 1997 Jabalpur; 1999 Chamoli; 2001 Bhuj; 2004 Indian Ocean; 2005 Kashmir; 2011 Sikkim) exemplify inadequate earthquake preparedness of the country. Out of the 60 % of Indian land that is prone to earthquakes, 26 % falls in Zone III[1] (Table 1) as per Indian Seismic code (IS 1893:2002). Vijayawada city is the only major city in Andhra Pradesh that falls in this zone. According to Bureau of Indian Standards (BIS), areas falling in this zone are predicted to be subjected to a ground acceleration of 0.16 g. The city of Vijayawada has been suffering mild tremors ($M_w < 3.5$) in the recent past (July 19, April 11, and January 26, 2012), accounting to be the seventh densest urban area by population density (27,300/ sq km) in the world and the fourth densest (in India) after Mumbai, Surat and Kalyan (Demographia World Urban Areas 2013). Also, with high percentage of population growth rate (48.5 % by 2021 from 2004), the seismic risk of the city increases (VMC 2006). Therefore, for the evaluation of seismic hazard, site characterization and ground response analysis are required for Vijayawada.

The scale of any hazard assessment procedure depends on the importance and geological location of the area. The geotechnical soil properties and the depth of the bedrock are the chief factors in the site response studies. Amplification of ground motion is highly dependent on local geological, topographic and geotechnical conditions. Local amplifications of unconsolidated sediments were responsible for intensity variations in ground motion during the 2001 Bhuj (Rajendran et al. 2001), the 1989 Loma Prieta (Seed et al. 1988) and the 1906 San Francisco (Borcherdt and Gibbs 1976) earthquakes. So, detailed geological and geotechnical characterization of Vijayawada region is to be carried out. Detailed site characterization and site-specific ground response analysis allow for assessing the parameters required to estimate site effects such as ground motion amplification, liquefaction, ground settlement/deformation and landslides.

Theoretically, ground response analysis can be conducted to estimate the peak acceleration suffered by the city. When instrumental testing is considered for estimation of local site effects, microtremor studies are much more feasible in highly dense areas compared to other methods. From microtremor studies, predominant frequency and amplification of soil can be assessed from the ambient noise of the ground. Though numerous factors contribute to earthquake damage, site amplification of ground motion and liquefaction take a leap over other factors in terms of their influence on damage potential. Liquefaction assessment can be carried out using different methods (deterministic, probabilistic, etc.) based on the availability and type of data, and liquefaction hazard can be estimated.

Depending on the geometry and loading conditions, different ground analysis in one-, two- or three-dimensional manners can be done. To capture the nonlinear cyclic response of soil within frequency domain solution, equivalent linear analysis was developed by Schnabel et al. (1972). Up to a strain of 10^{-3}, soil model can be simplified to an equivalent linear model. Equivalent linear method implies that strain always returns to a value of zero after cyclic loading and failure is out of scope. In a frequency domain analysis, it is assumed that modulus and damping properties are constant with time. For a given ground motion time history, propagation of ground motion is calculated using an initial estimate of

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[1] Zone III represents a moderate seismic intensity with an effective peak acceleration of 0.16 g.

Table 1 Zone factors and seismic intensity for different Indian seismic zones (IS 1893:2002, Clause 6.4.2)

Seismic zone	II	III	IV	V
Seismic intensity	Low	Moderate	Severe	Very severe
Zone factor (Z)	0.1	0.16	0.24	0.36

modulus (G) and damping ratio. The strain histories for each layer for which the maximum strain values are obtained are calculated. Effective shear strain equal to 65 % of the maximum strain is computed for a given soil layer, and corresponding shear modulus and damping are obtained from the curves. This process is repeated to achieve a converging solution. In the present study, a computer code "ONDA" (Ito and Towhata 2012) is used to calculate the shear modulus and damping ratio of each frequency component totally independent, thus providing a more precise assessment of soil behavior during earthquake loading. In this paper, ground motion parameters computed by ONDA were compared with the Microtremor results and found that results produced by ONDA are in good agreement.

To overcome any limitations in the theoretical analysis and for exact estimates of dynamic response, field testing can be performed. To estimate the site effects in moderately seismic regions with few ground motion records available, experimental method such as microtremor has been widely used. It is most advantageous as the recording time is quite short and facilitates the collection of data in very big and busy cities. Using microtremor testing, the predominant frequency and amplitude of vibration can be accurately estimated. The H/V (horizontal vs. vertical) method introduced by Nakamura (1989) is being widely used as it facilitates the recordings without the need for a reference site. When the horizontal spectrum is divided by the vertical spectra, the resulting curve shows a peak at the resonant frequency of the site and the corresponding amplitude of vibration. The disadvantage associated with the method is that it provides a lower-bound estimate of H/V amplitude (Kanai and Tanaka 1961; Lachet et al. 1996; Horike et al. 2001).

Liquefaction is a critical problem when the soil is subjected to high strain level during seismic ground shaking. Groundwater levels near the surface, magnitude of strain and soil type are the mobilizing factors of liquefaction. The liquefaction potential can be investigated by using different methods based on the field or laboratory data. The most widely used empirical method based on in situ tests is the standard penetration test (SPT). The framework for SPT-based assessments of liquefaction potential was at first proposed by Seed and Idriss (1971). This approach evolved over the time (Seed 1979; Seed and Idriss 1982; Seed et al. 1985; Liao et al. 1988; NCEER 1997; Youd and Noble 1997; Youd et al. 2001; Cetin et al. 2004; Idriss and Boulanger 2006; Juang et al. 2010; Franke and Wright 2013). In this paper, liquefaction potential of Vijayawada city is estimated using ONDA program. The tool uses SPT data to determine dynamic soil properties, and then, the peak ground acceleration (PGA) at surface is calculated at each location which is used for the evaluation of factor of safety against liquefaction. PGA and peak ground velocity (PGV) at surface are the best determinates of damage intensity during any seismic event. PGA and PGV at surface are important as they significantly vary from bedrock based on the local soil conditions. Liquefaction potential is estimated in accordance with Highway Bridge Design Code (Japan Road Association 2002), and liquefaction hazard map of the city is developed.

2 Site characterization

Vijayawada city is located at 16.52°N Latitude 80.62°E Longitude and is the third most populated metropolitan area in Andhra Pradesh (fifth largest state in area and population). It occupies an area of about 73 km^2. The geographical limits of the city considered for the study are based on population density and land use (Fig. 1). The topography of the city is almost flat with weathered outcrops of average elevation of about 13 m above MSL. Krishna River forms a dominant part of the geography of Vijayawada and runs through the city. Three canals originating from the north side of the Prakasam barrage reservoir, Budameru (Eluru), Bundar and Ryves, run through the city. Diverse lithological formations from the age of Archean crystallines to recent alluvium are present. The city is mostly covered by recent alluvium. The thickness of the alluvium in some of the areas is estimated to be of the order of 150 m. Geological Survey of India (GSI) carried out deep drilling at some locations in the city and could not find the bedrock depth up to 140 m below the ground. But, at some of the locations near the outcrops, bedrock is available at a depth of 20–30 m below the existing ground level. The upland parts of the city in the east, northeast and southwest comprise rock outcrops of Khondalite/charnockite lithology (Fig. 2).

India has a total of more than four hundred major faults which influence seismic hazard in India, and also faults in neighboring countries can cause seismic hazard in India. The city of Vijayawada is located in Peninsular India (PI) which covers almost one-third of Indian subcontinent. The seismicity of PI was assumed to be relatively low until the advent of Latur (1993, $M_w = 6.1$) (Gupta et al. 1993) and Jabalpur (1997, $M_w = 5.8$) earthquakes (Jain et al. 1997). The Latur earthquake occurred in zone-I (IS 1893:1984) which has the maximum expected acceleration of 0.1 g and intensity of V[2] on MM scale, whereas the actual intensity reached VIII.[3] Unlike Latur, Jabalpur earthquake had intensity of damage (VII[4]) almost close to that suggested by code (VIII). The 2001 Bhuj earthquake ($M_w = 7.7$) is the most damaging earthquake in India located in PI. This event was considered one of the stable continental regions (SCR) before 2001 (Rajendran et al. 2001). All the three damage locations discussed above were covered by thick alluvial deposits. After these events, the seismic code of India was revised in 2002 and according to which no zone in India landmass was marked as seismically safe.

Due to the subduction of Burma plate toward the Bay of Bengal, seismic activity in the eastern part of south India and Bay of Bengal has increased resulting in reactivation of older faults and development of new faults (Reddy and Chandrakala 2004). Vijayawada city does not have a record of any major earthquake but has been experiencing mild tremors during different events in 2012 [epicenters at Northern Sumatra (VI[5]); Sattenapalli (II[6]); Unknown (V)] and in the past (June 2010, IV; August 2009, V; May 2008, II; March 1967, VII) to in situ fault adjustments (Table 2). Among the South Indian shield, Cuddapah Eastern Margin (Fig. 3) has the most striking seismicity. It is located between the Cuddapah and Krishna Godavari Basin. Nearly 65 (1800–1991) events were recorded in this

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[2] Description for the level of intensity on MMI scale.
  V: Felt by almost everyone, some people awakened. Small objects moved. Trees and poles may shake.

[3] VIII: Little damage in specially built structures. Considerable damage to ordinary buildings, severe damage to poorly built structures. Some walls collapse.

[4] VII: Slight to moderate damage in well built, ordinary structures. Considerable damage to poorly built structures. Some walls may fall.

[5] IV: Felt by many indoors, few outdoors. May feel like heavy truck passing by.

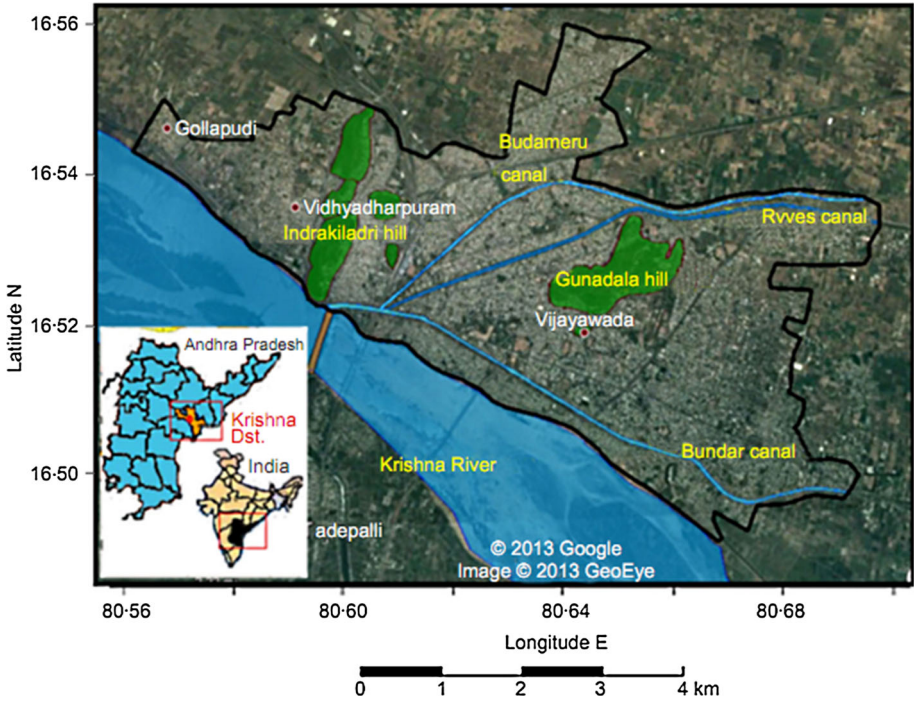[6] II: Felt by a few people, especially on upper floors.

Fig. 1 Location map of Vijayawada (Manne and Satyam 2013)
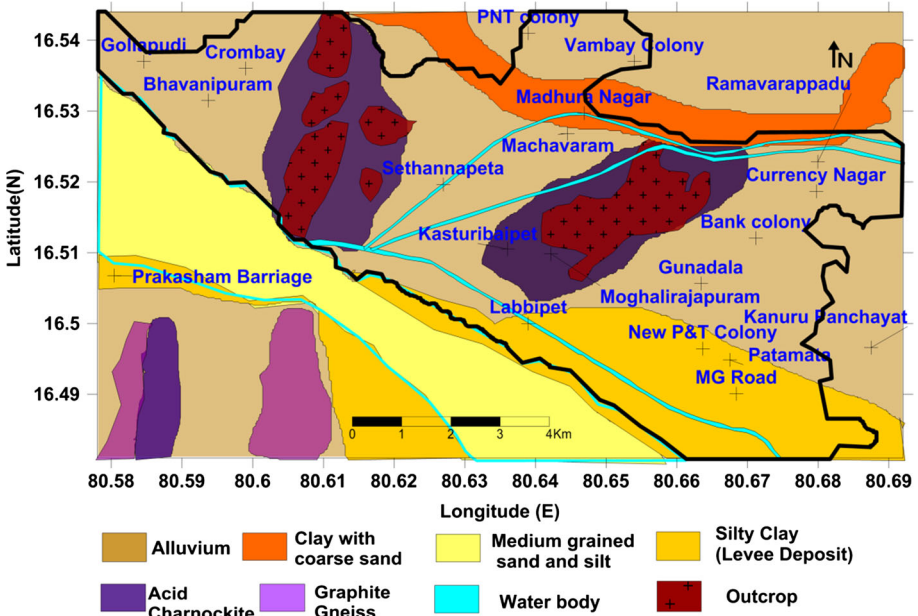

Fig. 2 Geological deposits of the study area with major lithologies

Table 2 Details of seismic events in and around Vijayawada region after 2009

Year	Epicenter	Magnitude	Intensity (MMI)	Lat (N)	Long (E)	Depth (km)	Distance (km)	Source
2013	Ongole	2.9	–	15.5	80.0	5	–	IMD
2012	Sattenapalli, Guntur	M_w 3.7	II	–	–	–	52	Deccan Chronicle, The Hindu
2012	Off West Coast of Northern Sumatra	M_b 8.1	VI	00.80	92.40	18	2172.7	IMD, Economic Times
2011	Annaram, Khammam	M_d 3	–	17.48	80.70	7.6	–	NGRI
2010	SW of Teressa Island	M_w 7.5	IV	07.75	91.94	35	1568	ASC India
2010	Ramakrishnapuram, Khammam	M_L 2.6	–	117.20	880.60	43	–	NGRI
2010	Kothagudem, Khammam	M_L 3	–	117.52	880.68	0.1	–	NGRI
2009	W of Little Coco Island	M_w 7.6	V	14.01	92.92	33.1	1348.2	ASC India

IMD Indian Meteorological Department, *NGRI* National Geophysical Research Institute, *ASC* Amateur Seismic Centre
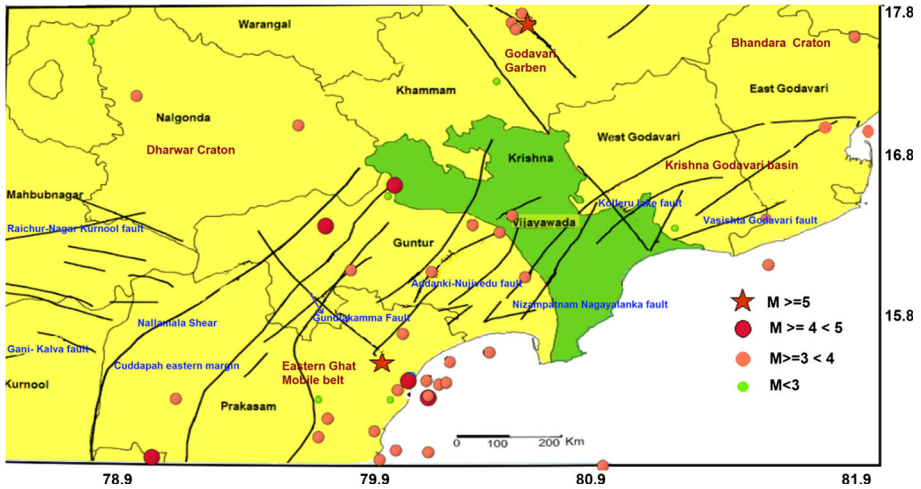
Fig. 3 Map showing epicenters and seismic events (1800–2014) close to Vijayawada city
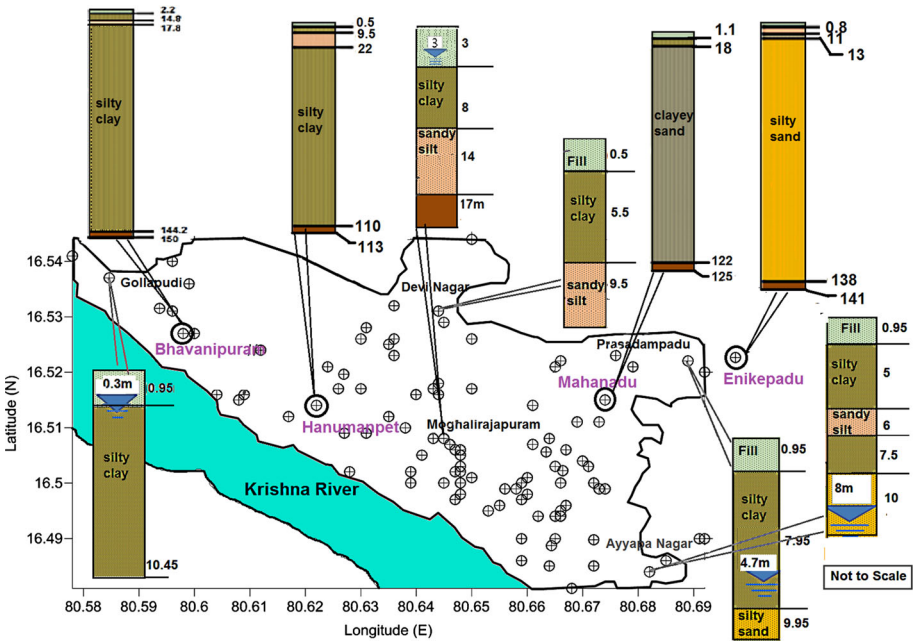

Fig. 4 Locations of boreholes used for the study

area (SEISAT 2000). The strongest earthquake recorded in Cuddapah Eastern Margin region is the Badrachalam earthquake (SEISAT 2000). The 1969 Badrachalam earthquake (M_s 5.7) and 1967 Ongole Earthquake (M_s 5.3) are the strongest earthquakes in the southern peninsula which occurred at 25 km in the lower crust and within upper crust, respectively (Srinagesh et al. 2012). The maximum observed intensity was VII on MMI

scale for these earthquakes (Mathur 1998). The 1969 quake interrupted the functioning of the Kinnersani reservoir temporarily. Around 22 seismic sources around the city are identified. Figure 3 shows different seismic events that occurred from 1800 to 2012 in the regions near to city and also the faults. The prominent active fault is the Gundlakamma Fault (Fig. 3), and it trends in a NW–SE direction for 100 km. Continuous seismic activity was recorded during 2008–2010 along the fault, and also earthquakes of magnitude (M 4–5) and tremors ($M \leq 2$) are recorded frequently (Srinagesh et al. 2012).

3 Geotechnical details

Site characterization can be done by geological data, geophysical testing or using geotechnical data. About 296 borehole data were collected from different organizations; the data are well scattered along the city (Fig. 4). These data points are spread throughout Vijayawada urban and some rural locations such as Enikepadu, Kanuru, Nunna, Gollapudi and Ibrahimpatnam. The collected data were then synthesized and were brought to a common platform required for geotechnical characterization. Most of the data available are up to a depth of 10–20 m below the existing ground level. Deep borehole data up to bedrock are available at very few locations which includes Enikepadu, Mahanadu Road, Hanumanpet and Bhavanipuram (Fig. 4). The geotechnical data show that the study area has four major soil types, namely black cotton (58 %), sandy clay loams (23 %), red loams (17 %) and sandy soils (2 %). Most of the city is covered by alluvium, and sandy clay loams are formed along river. The northern perimeter consists of black clay with coarse sand. Few outcrops made up of acid charnockite and garnet silliminite can be located as shown in Fig. 2. Another classification based on the borehole data consists of four major soil strata in the city which includes sandy silt, silty/sandy clay, silty/clayey sand and rock. In the southern region of the city, silty clay, sandy silt and silty sand are highly predominant. In the northern side, silty clay and sandy silt are abundant. Eastern parts consist of silty clay up to a depth of 5 m and silty sand from 5 to 8 m. In the south, in a few places, hard rock is present at a depth of 5 m and in the other locations in the western part, sandy silt and silty clay are prevalent at 2–5 m and silty clay below 5 m. Southern and eastern blocks also consist of seams of clayey sand mostly occurring under sandy silt layer.

Groundwater level influences the ground response significantly and hence cannot be neglected for evaluation of site effects. Evernden and Thomson (1985) deduced increment of intensity of shaking based on water table depth. Dupré and Tinsley (1990) classified soil susceptibility to liquefaction based on water table depth, and also Yang and Sato (2000) identified that vertical-component motions may significantly be affected by pore-water saturation of soils. Water table levels are shallow (0–2 m) in the southern and south western locations. In most of northern and western locations, the water table depth varies from 2 to 4 m. In a few areas, the water table is more than 6 m below the ground level. It can be outlined that the northern and western parts of the city mostly have shallow water depth, which infers their location in the upstream side of the river. Southeastern, northeastern and southern parts of the city have water table depth ranging from 4 to 6 m. Figure 4 shows a few locations with soil scatter at different depths with water levels and also deep boreholes up to 150 m.

4 Ground response analyses

The damage pattern in urban areas during an earthquake depends on the characteristics of the event and on the interaction between site response and vulnerability of the exposed structures. Most of the urban settlements have occurred along river valleys with soft and young soil deposits which were prone to serious damage during earthquake. Vijayawada city is located along the stream of Krishna River and is covered by dominant amounts of alluvium. Ground response analysis will be useful for the prediction of local site effects and to estimate the dynamic behavior of the soil during seismic loading.

For ground response analysis, the equivalent linear approximation of layered soils to compute the seismic response of horizontally layered soil deposits is widely used as it does not require much computation time and detailed soil data. This is due to the usage of single value of stiffness and damping for all frequency components. Equivalent linear approximation method (ELM) provides best results for low strain levels and when soil does not reach its available shear strength. Nevertheless, the conventional ELM can have limitations when dealing with thick deposits of alluvium or soft soil. ELM cannot estimate the shear modulus and damping ratio correctly when the range of high frequencies >10 Hz is considered (Sugito et al. 1994). SHAKE (Schnabel et al. 1972) program uses the same shear modulus (G) and damping for all frequency components irrespective of the strain amplitude, due to which peak accelerations are underestimated. Sugito et al. (1994) developed software named FDEL considering characteristic of frequency-dependent material properties. Note that this method uses a new parameter named average equilinear strain defined for each frequency component. Using this parameter, dynamic response for each frequency component can be calculated. It was shown that FEDL can take into account better values of shear stiffness and damping ratio.

In this study, the analysis was performed using modified one-dimensional equivalent linear dynamic analysis code ONDA (Ito and Towhata 2012). For the analysis, the shear modulus and damping curves were generated using the empirical formula obtained from the curves given by Yasuda and Yamaguchi (1985). Figure 5 shows the curves used at different soil layer depths at Ayyappa Nagar site. Bhuj earthquake ($M_w = 7.7$ and PGA = 0.38 g) on January 26, 2001, was selected as the input ground motion (Fig. 6)
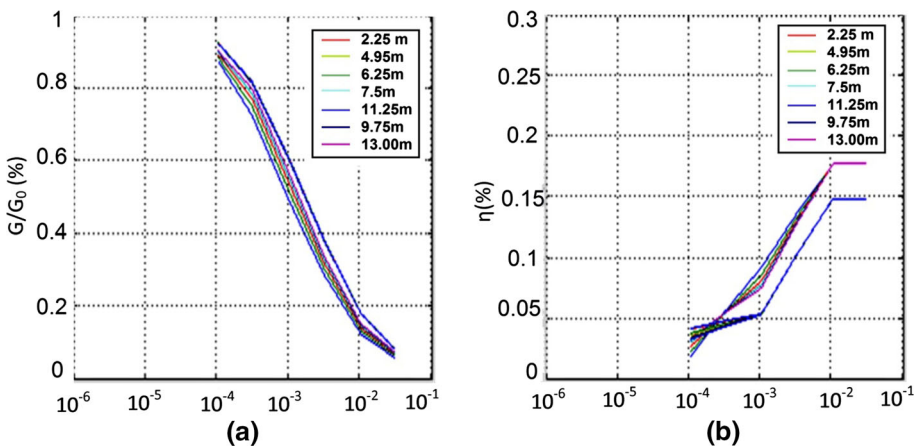

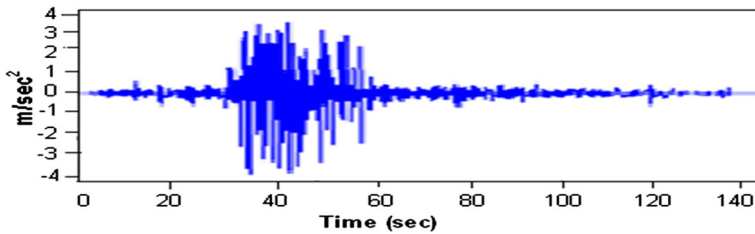**Fig. 5** **a** G/G_0 and **b** damping curves used at Ayyappa Nagar site

Fig. 6 Acceleration time history of input ground motion [Bhuj earthquake, 2002; M_w = 7.7 (Ahmadabad), PGA = 0.38 g, PGV = 9.3 cm/s] at a depth of 150 m
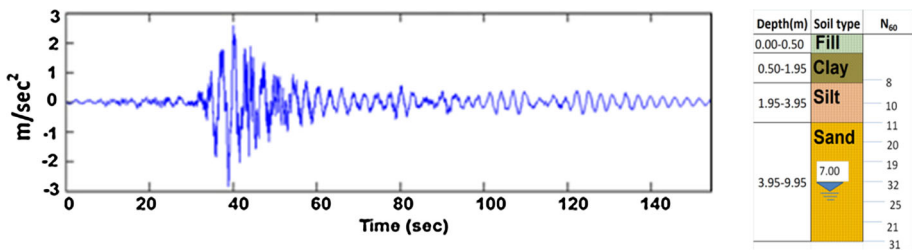

Fig. 7 Acceleration time history at surface at Ayyappa Nagar site (PGA 0.23 g, PGV = 8 cm/s)

which occurred at a depth of 150 m. The surface time history obtained from the analysis for Seetharamapuram area is shown in Fig. 7.

From the detailed site-specific analysis, PGA (surface) at different locations are calculated and shown in Fig. 8. These values are in the range of 0.07–0.285 g. By comparing the available water table data with estimated PGA, it was observed that the accelerations are very high (>0.18 g) in the locations of sand with a water table depth >4 m. Values of 0.1–0.18 g were estimated at different locations having water table depth ranging from 2 to 4 m. These locations were characterized by clayey sand and mixture of sand, silt and clay. The acceleration levels were observed to be very low (<0.1 g) in northern, western and few locations in south. These locations have shallow water table of <2 m and soils with layers of silty sand and silty clays.

Usually, peak acceleration is related to the extent of structural damage as it produces inertia force in the structures (Kramer 1996). From past case histories, it can be inferred that high PGA levels are not exactly responsible for the complete damage (2010 Canterbury, 1.26 g; 2011 Christchurch, 2.2 g). PGV is the potential parameter to measure damage compared to PGA (Ito and Towhata 2012). This is because low-frequency content of the ground motion caters for the displacement and high-frequency content imparts the acceleration in the structure and also PGV is not specifically dominated by any frequency. Peak velocity (PGV) can also be related to the strain induced and has also been employed for the estimation of liquefaction potential, and damage to buried pipelines due to earthquakes by few researchers (Ito and Towhata 2012; Akkar and Özen 2005; Wu et al. 2003). Fujimoto and Midorikawa (2006) and Wu et al. (2003) considered PGV as a parameter to estimate the intensity of seismic damage, apart from considering magnitude.

In this paper, in order to estimate the damage distribution, peak velocities and displacements have been calculated at all locations by integrating acceleration time history at
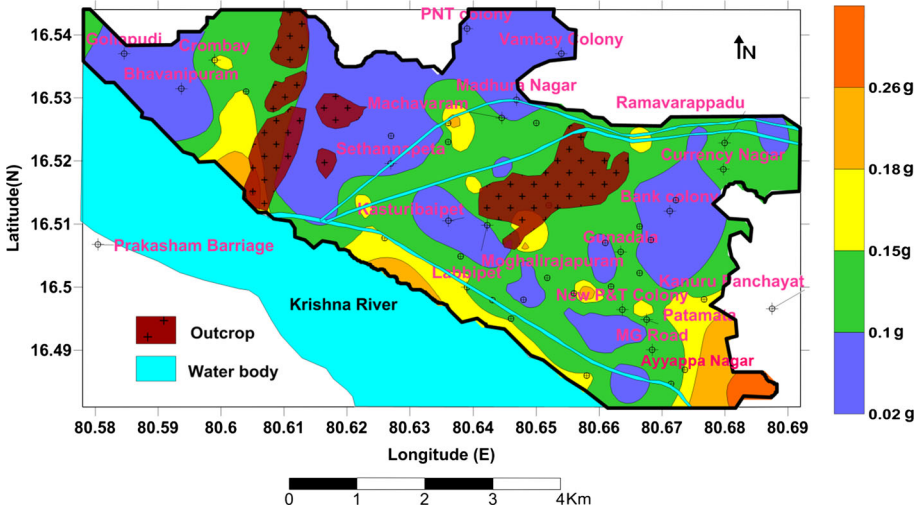
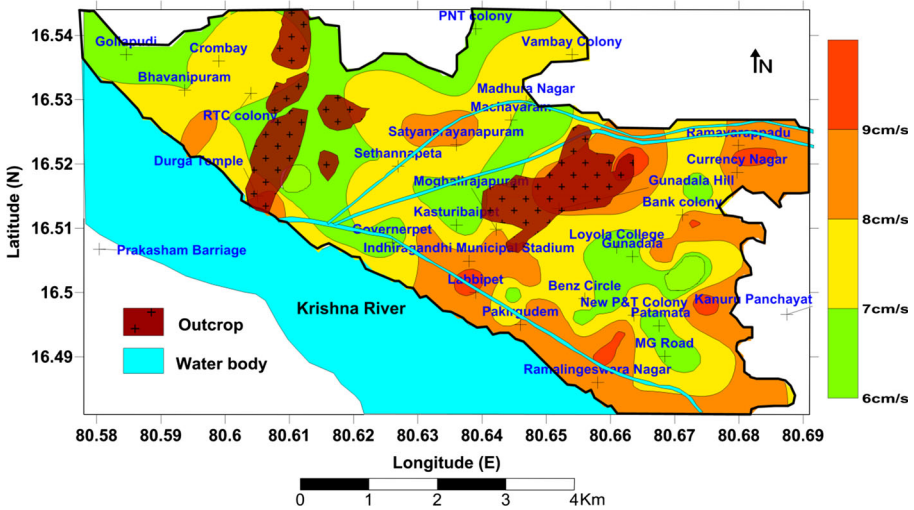**Fig. 8** Map showing PGA (surface) values at different locations

Fig. 9 Map showing the PGV at different locations in Vijayawada city

the ground level. From the analysis, high velocity (>8 cm/s) concentrations are in the eastern and southern locations (Fig. 9). Therefore, the damage intensity may be higher in these parts of the city. The high velocity region (orange) is mostly concentrated along the canals and southern side of river. Most parts of the city have peak velocities in the range of 6–8 cm/s. The outcrop regions in the northern area have comparatively low velocity of vibration (8–6 cm/s). The developed map can be further used for the damage estimation for the city in case of seismic event when coupled with the factor of safety against liquefaction.

5 Microtremor testing

To estimate the peak frequency and amplitude of vibration, microtremor testing was adopted in the area of study. In Vijayawada, the experimental program was carried out at 75 different locations (Fig. 10). The total microtremor setup consists of a MR2002-CE Recorder Unit, MS2003+ velocity sensor from Syscom Instruments (http://www.ptmitra.com/mitra-syscom.html) with a mounting plate and other related cables. The MR2002-CE is a compact triaxial vibration recorder. Care needs to be taken for obtaining quality data. The instrument must be placed on a levelled, dry ground away from high buildings and underground structures. Heavy winds have to be avoided to prevent erroneous data. The locations are selected in a grid of 500 m × 500 m. The tests were conducted in early mornings and late evenings when the disturbances (heavy vehicle movement, blasting, loud speakers, etc.) are comparably low. The duration of the records to be obtained depends on the minimum expected frequency. Usually, a duration of 2–30 min is required if the expected frequency range is of 10–0.2 Hz. The vibrations are recorded for duration of 60 min at each test site, and for recording, the exact location of the test site GPS was used.

The recorded data sets can be analyzed to identify the peak frequency and H/V amplitude. VIEW 2002 was used to analyse the recorded data using Nakamura (1989) technique (H/V method), and the city was classified into three zones based on peak frequency, shape of curve and soil type. Figure 11 shows the H/V amplitude versus frequency plots at some test locations (shown in Fig. 10 in color purple) along with the proposed classification. The response spectra of the predominant frequency ≥4.0 Hz are classified as type I, which indicate thin sediments. The response spectra in this classification are characterized by the multiple peaks toward the left of origin. Most of the central and eastern parts (52 % out of the total test sites) of the city fall under this category. Eastern parts of the city are covered by silty clay, sandy clay and sandy silty, and predominant soils
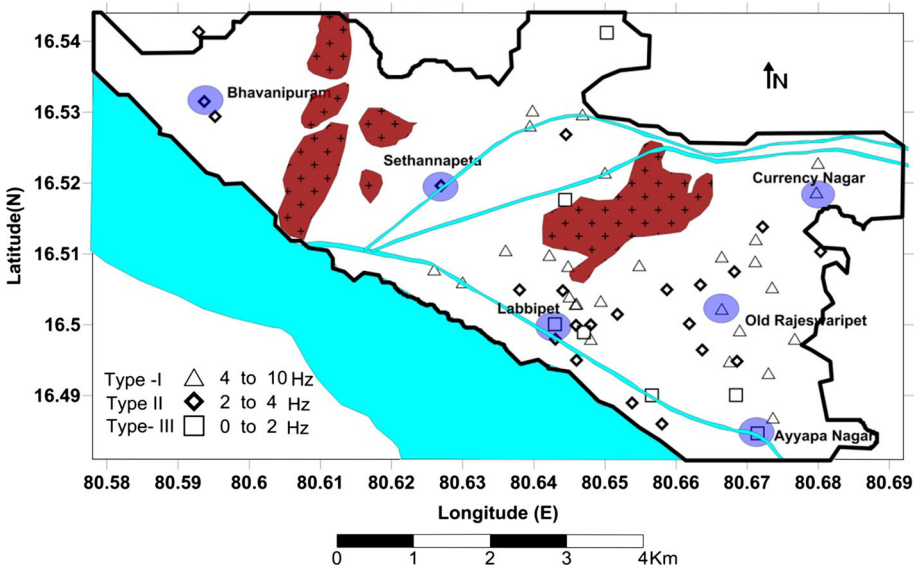

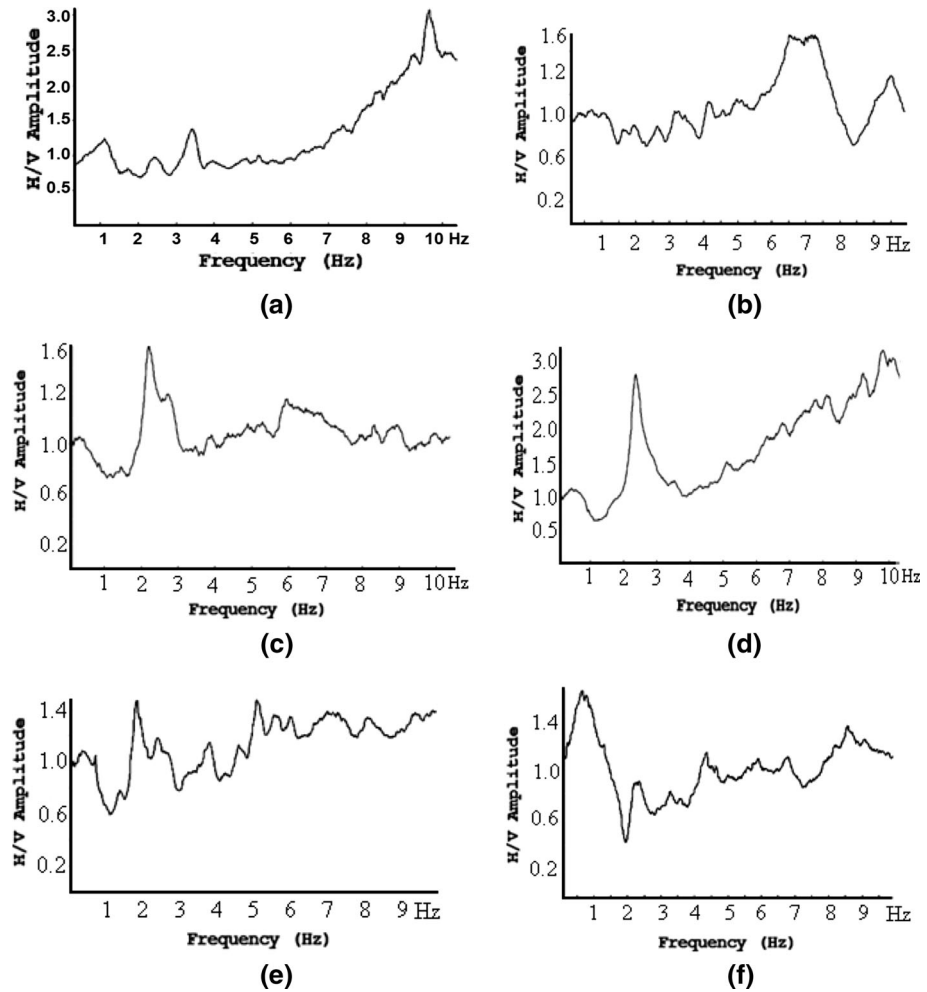**Fig. 10** Microtremor testing locations and classification types

Fig. 11 Classification of microtremor recordings. **a** Currency Nagar (I), **b** Old Rajeswaripet (I), **c** Bhavanipuram (II), **d** Sethanapeta (II), **e** Labbipet (III), **f** Ayyappa nagar (III)

in this type are silty clay and silty sand at depth more than 5 m. Maruthi Nagar and Old Rajeswaripet (Fig. 10) which fall under this category (Fig. 11a, b) have silty clay up to 10 m, and SPT values range from 4 to 21. The high amplitude (>2) in these locations infer high impedance contrast between the bedrock and sediments. The response spectra peaks of medium frequency (2.0–4.0 Hz) are categorized as type II. In total, 35 % of the test locations fall under this category. Also these locations have clearly distinct peaks that indicate high impedance contrast. Almost the total western parts and southern part of the city exhibited such frequencies. The predominant soil of the locations in this category is sandy silt and silty clay. The response curve of this type has strikingly differentiable peaks (Fig. 11c, d). Also these locations have SPT N ranging from 5 to 12 up to 10 m depth. The type III classification has low-frequency peaks (<2.0 Hz) which have a mix of clayey sand, silty sand and silty clay. The locations such as Bhavanipuram and Ayyappa Nagar which

fall under this category have SPT N ranging from 16 to 22. Such peaks indicate the presence of thick sediments.

From the H/V analysis, the peak amplitude is obtained and the H/V amplitudes were identified to be in the range of 0.31–3.6. It has been interesting to observe that the amplitudes are in the range of 1–2 for the locations along the river and surrounding the canals (Ryves and Budameru) which fall in type I, whereas higher amplitudes (2–3) have been observed in the eastern parts (type II) of the city.

Predominant frequency is observed to be high in the areas of high density (VMC 2011). It is low in areas of thick and very soft sediments. From the analysis, it can be inferred that low-frequency (2–4 Hz) regions are those occupied by soft alluvium or silty clay (Fig. 2). Most of the southern and eastern regions that are occupied by mixture of sand and silt are representative of high frequencies (≥4 Hz). Resonant frequency varies inversely with thickness of sediment, and so it might be assumed that the thickness of soil layer is high in western and some southern parts along the river. To understand the dependency of the instrumental frequency, the values are compared with the site-specific ground response analysis.

Figure 12 compares the peak spectral amplitude and the peak frequency values obtained from the detailed ground response analysis using ONDA with microtremor testing. It is evident from Fig. 12a that the H/V amplitude at the peak is always lower than the spectral ratio. In contrast, the frequency values from both analyses coincided. This infers that the peak frequency values estimated for the city from both the analyses are reasonable. Comprehensively, it can be concluded that buildings in the southern and eastern halves of the city suffer damage due to seismic waves of higher frequency and those in the rest of the parts would suffer damage due to lower frequency. From the results, it is imperative that buildings that have a predominant frequency equal to 4 Hz are susceptible to damage especially in the regions such as Rajeswaripet (south) and Maruthi nagar (east). It is advisable to construct buildings with natural frequencies that contrast the findings to avoid serious damage.
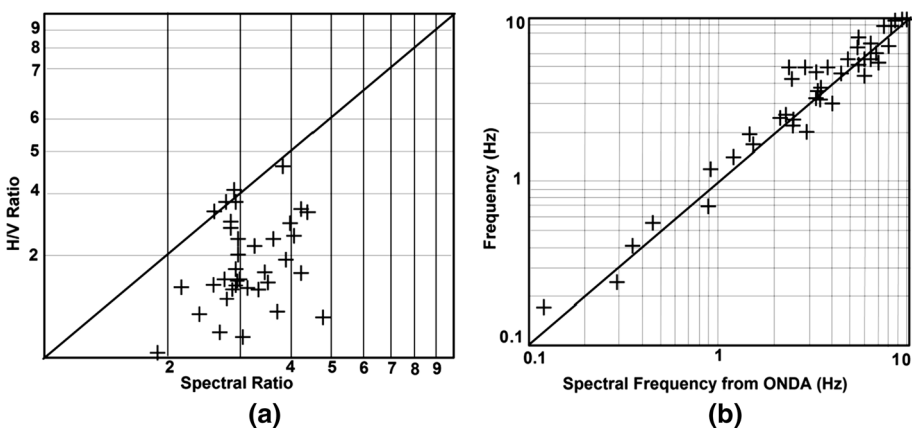

Fig. 12 Comparison of H/V amplitude and frequency from microtremor testing with the amplitude and spectral frequency from ONDA (**a** amplitude and **b** frequency)

6 Liquefaction hazard

Liquefaction-induced ground failure is one of the major causes of damage due to earthquakes. Massive and important structure, such as bridges, nuclear reactors, etc., suffers critical damage due to initiation of liquefaction during seismic ground shaking. Moreover, the concentration of alluvial deposits in Vijayawada city greatly influences the site response during shaking. Large amount of sandy stratum gives way for the occurrence of liquefaction. Assessment of liquefaction susceptibility provides a preliminary idea of the resistance of soils in the study area to liquefaction. Tsuchida (1970) introduced the identification of liquefaction susceptibility using grain size distribution (GSD) curves. Numata and Mori (2004) updated the ranges using Japanese liquefied soil data after 1987. With decrease in grain size for poorly graded soils and with increase in grain size in well-graded soils, liquefaction resistance decreases. This is due to the absence of clay minerals for cohesion and decrease in permeability, respectively. The limiting curves given by MoT (1999) were used to identify areas susceptible to liquefaction potential. Figure 13 shows different locations that are susceptible to liquefaction hazard.

After the assessment of liquefaction susceptibility at several locations, potential of liquefaction was calculated using the SPT-based method in Highway Bridge Design Code (Japanese Road Association 2002). Surface PGA estimated from ONDA at different locations was used for estimating liquefaction hazard. Liquefaction is likely when the cyclic stress ratio exceeds cyclic resistance ratio (determined by SPT N and grain size). From the method, it was identified that no liquefaction (Fig. 14) was observed in the northern, northwestern and eastern parts of Vijayawada. Averaged values of F_L up to a depth of 15 m are shown in Fig. 14. Estimation of local site effects and liquefaction potential is a preliminary step in the microzonation studies. So, this study is helpful to assess the engineering geological and geotechnical characteristics and to understand seismic hazard of the city. The results can be used for establishing seismic microzonation of the city and eventually in developing codes that ensure the safety of engineered structures.
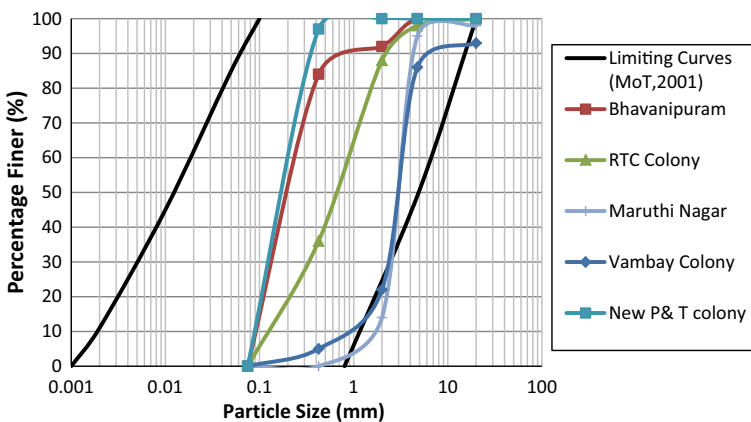

Fig. 13 Grain size distribution (GSD) curves at different locations (at 10 m depth) with limiting liquefaction curves
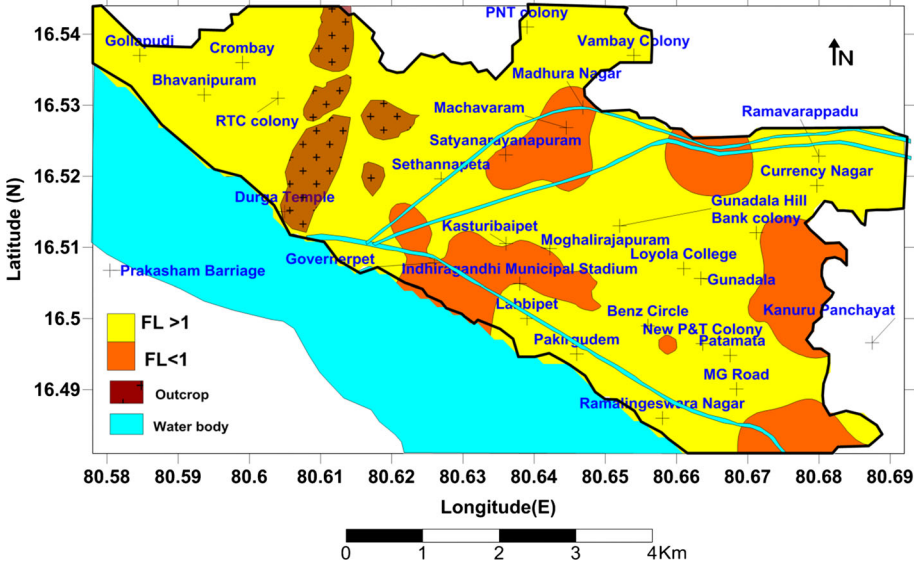
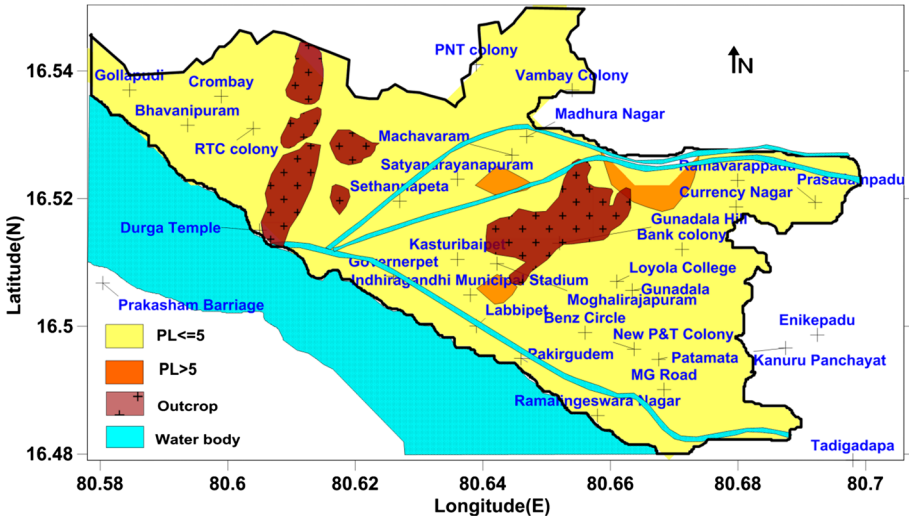**Fig. 14** Liquefaction hazard map of Vijayawada city (F_L was averaged in the top 15 m)

Fig. 15 Distribution of evaluated liquefaction risk (P_L)

The factor of safety against liquefaction (F_L) results in identification of sites with potential of liquefaction but does not brief on the significance. This problem is solved by evaluating liquefaction damage index which specifies the severity of damage in a specific site due to liquefaction. The damage index (P_L) was evaluated by the Tatsuoka et al. (1980) method as shown in Eq. (1). Figure 15 illustrates the distribution of liquefaction damage index (P_L).
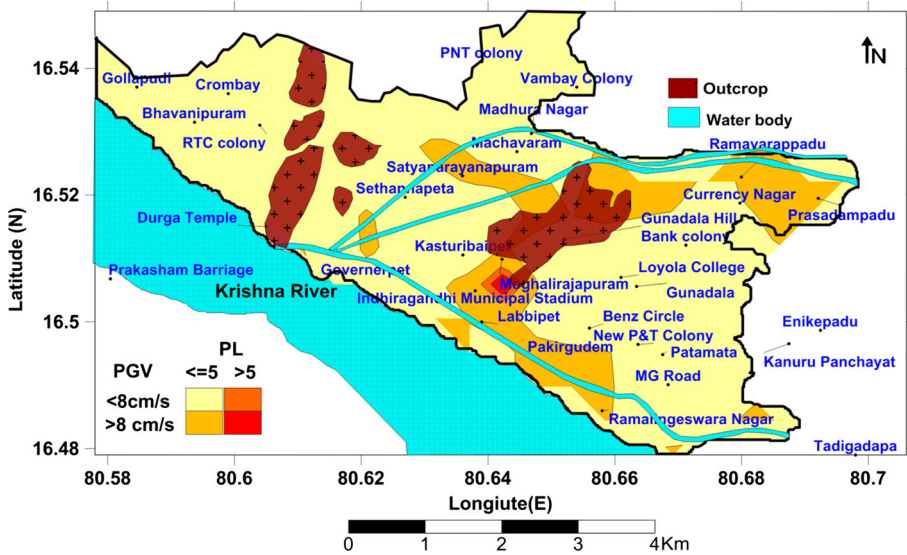
Fig. 16 Estimated damage distribution rate by earthquake shaking and liquefaction

$$P_{\mathrm{L}} = \int\limits_0^{20} F(F_{\mathrm{L}})(10 - 0.5Z)\mathrm{d}Z \tag{1}$$

where $F(F_{\mathrm{L}}) = 1 - F_{\mathrm{L}}$ if $F_{\mathrm{L}} < 1$ else, $F(F_{\mathrm{L}}) = 0$.

Almost half of the city falls under low-damage category. Almost all the locations that are near the water bodies are in the zone of risk. Complete northern and northeastern parts are potentially liquefiable sites. To understand the damage distribution of the city, a combination of structural damage (PGV) and liquefaction (P_{L}) is illustrated in Fig. 16. Ranges of these two parameters are divided into four categories and mapped. The most vulnerable location is marked in red and the least vulnerable site in yellow. It is observed that the western and southern regions of the city are subjected to least damage. The western part having the least damage can also be attributed to the lack of more of borehole data when compared to the other parts of the city. Locations to the north, west and south of Gunadala hill are more susceptible to damage.

7 Conclusions

The city of Vijayawada has been identified as an essential location to carry out seismic ground response analysis after investigating the seismic, geological and geotechnical characteristics of the city. The presence of recent alluvium and higher groundwater levels have led to the assessment of liquefaction potential. The ground surface Fourier spectra produced by the site response analyses were studied using the equivalent linear method, and classification was done based on the acceleration levels.

The city was identified to be prone to PGA of up to 0.27 g when the bedrock is subjected to acceleration of about 0.38 g from the analysis using ONDA. To understand the intensity of damage, the PGV was also calculated and the city is associated with an average

velocity of up to level of 8 cm/s. To identify other reliable parameters such as amplification and peak frequency, microtremor testing was conducted in the city and three different zones were identified. Most of the city falls under high frequency range, i.e., ≥ 4 Hz. So, building that have a natural frequency near to 4 Hz is susceptible to damage in these regions. After detailed ground response analysis using equivalent linear analysis and microtremor testing, the values of frequency and amplitude were compared. In the comparison, it was evident that peak frequency coincides with the calculated value, whereas H/V amplitude provides a lower-bound estimate.

For the identification of the liquefaction susceptibility of Vijayawada, GSD curves were developed and the locations falling in the limiting range were identified. To demarcate the potential sites, SPT-based empirical method proposed by Highway Bridge Design code was used to calculate the factor of safety against liquefaction. To further estimate the damage, liquefaction potential index (P_L) and map with comparison of PGV and P_L was generated. So, the study is eventual in generating preliminary microzonation maps which can be used for general planning purposes and for disaster management plans.

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