



# Ground response analysis and liquefaction hazard assessment for Vishakhapatnam city

Swathi Priyadarsini Putti<sup>1</sup> · Neelima Satyam<sup>1</sup>

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## Abstract

Liquefaction is a complex phenomenon where the soil is subjected to high strain levels due to dynamic loading at the time of seismic events, contributing to severe damage and collapse of the structures. The effect of liquefaction can be predicted in three stages, i.e., evaluation of susceptibility, hazard and deformations. Soil susceptibility to liquefaction can be assessed using the geotechnical properties such as grain size, age of the soil deposit, penetration resistance of the soil, whereas hazard can be assessed in terms of factor of safety estimated against liquefaction. In the present study, one-dimensional equivalent linear ground response analysis has been carried in the study area Vishakhapatnam, Andhra Pradesh (India) and the surface peak ground acceleration (PGA) has been estimated using DEEPSOIL. The surface PGA values obtained have been used in liquefaction hazard assessment using stress-based method (SBM) and energy-based method (EBM). Hazard maps were generated from the estimated values of PGA and factor of safety against liquefaction ( $F_L$ ). The surface PGA values obtained are in the range of 0.09–0.14 g which are higher than 0.1 g (limiting value provided by Seismic code of India (IS: 1893-2002)). It is observed that the locations in the central part of the city are prone to higher accelerations comparatively. From liquefaction potential assessment, it is evident that most of the locations in northern and central parts of the city are prone to liquefaction. As the study area has two operational ports and is highly industrialized, findings from the present study will be helpful in retrofitting, analysis and design of structures, therefore, solving practical challenges in structural and geotechnical engineering.

**Keywords** Seismic energy · Earthquake · Liquefaction potential · Surface peak ground acceleration · Excess pore pressure

## Introduction

India has experienced many devastating earthquakes with various magnitudes from the past. After the occurrence of Latur earthquake ( $M_w = 6.2$ , 1993), Jabalpur earthquake ( $M_w = 6.1$ , 1997) and Koyna earthquake ( $M_w = 6.0$ , 1967) in seismically inactive and stable Peninsular region of India, seismic codal provisions have been revised. Further, no region of India is considered to be stable and safe seismically. Though hazard maps were provided extensively for all the parts of the world in terms of PGA, slope stability,

landslide hazard, etc. It is evident that these macro solutions are not reliable in the prediction of hazards from past events. Therefore, in this study, an attempt has been made to provide site-specific hazard maps in terms of liquefaction hazard and surface PGA for the study area Vishakhapatnam city (India). Visakhapatnam is the first largest city with two operational ports (Vishakhapatnam port and Gangavaram port) in Andhra Pradesh and third largest city on the eastern coastal belt after Kolkata and Chennai [27]. Visakhapatnam has turned out to be an Industrial and trade center in the entire south of India because of its ports. Seismic history, rapid industrialization, poor quality control and construction practicing, increased population growth rate and infrastructure development makes the study area highly susceptible to damage due to seismic events. Thus, the prominence of the city in terms of population, industrialization and economy motivated to undertake present research.

Extensive geotechnical data have been collected for locations covering all over the city. One-dimensional ground

✉ Swathi Priyadarsini Putti  
pspdarshini@gmail.com  
Neelima Satyam  
neelima.satyam@gmail.com

<sup>1</sup> Geotechnical Engineering Laboratory, EERC, International Institute of Information Technology, Hyderabad 500 032, India

response analysis has been carried out using DEEPSOIL [44] to estimate PGA at ground level and bedrock using the equivalent linear method. Using the surface PGAs from the ground response analysis and available geotechnical properties (Density, shear wave velocity, SPT-N value etc.) of the soil, liquefaction hazard has been estimated for the study area. An effort has been made to generate hazard maps indicating liquefaction hazard based on the obtained results. Though the results from SBM are not comparable with those of EBM, it is observed that the results from EBM suggest the soil to be liquefiable in contrast to that of SBM at many locations of the study area. Many sites are identified to be likely to liquefy due to the presence of silty sand and fine sand with water table at shallow depths. Hazard maps generated from the current study will be a great tool in engineering practice. Liquefiable sites can be identified and mitigation measures can be adopted such as soil modification and stone columns against liquefaction.

## Details of the study area

Visakhapatnam is the Financial Capital of the state Andhra Pradesh (India) and is the administrative headquarters of Visakhapatnam district and Eastern naval command. The core part of the city along with its surrounding locations constitutes Visakhapatnam Metropolitan Region with a population of 1,800,000. Geographically the city lies in the eastern part of Southern India between the Eastern Ghats mountain ranges and the Bay of Bengal coast at  $17.68^\circ$  North latitude and  $83.21^\circ$  East longitude. Narava hills, Kailasa hill range and Yarada hills are the boundaries of the city on western, northern and southern parts respectively.

## Geology and ground water table

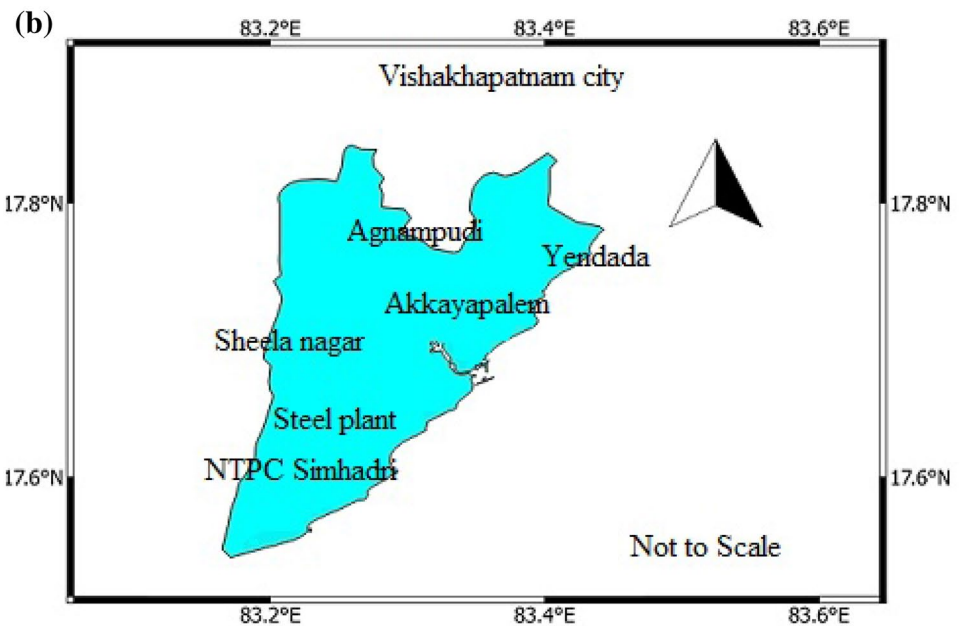
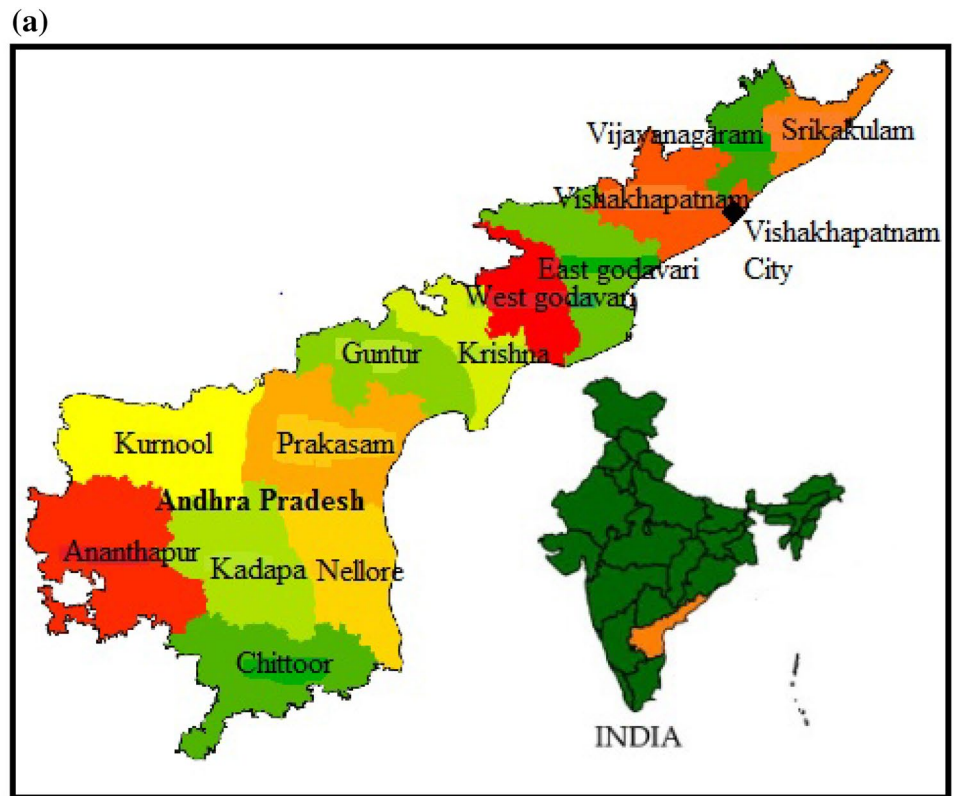
The groundwater table depth ranges from less than 3 m and greater than 14 m below ground level with flow of groundwater from higher to lower elevations [38]. This is due to the varying subsurface conditions and topography at different places in the study area. Among the dominant rocks types existing in the study area; it has been observed that Khondalite rock formation areas are the most favorable for groundwater exploration. The reason may be highly weathering and fracturing nature of the rock than the other types of rocks. Quartzite is the next promising rock type that has good water holding capacity and is also prone to high fracturing because of its brittleness. Charnockite and Leptynite rock formations are the poorest water holding zones because of their low weathering and fracture nature. As khondalite is the dominant rock mineral present in the study area, groundwater is available at most of the parts of the city. The

political boundaries of the city along with geological formations are presented in Fig. 1.

## Seismicity details

The state of Andhra Pradesh (India) has experienced three major earthquake events namely, Vijayanagaram (1917,  $M_w = 5.5$ ), Ongole (1967,  $M_w = 5.4$ ) and Bhadrachalam (1969,  $M_w = 5.7$ ). The eastern coastal belt of the state is characterized by many faults and fractures, making the state susceptible to seismic activities. Seismicity in the eastern coast of India and Bay of Bengal has rapidly increased due to Burma plate subduction towards Bay of Bengal, which further led to the creation of new faults and reactivation of inactive faults [28]. Vishakhapatnam also has major faults namely Vamsadhara, Nagavali, Polavaram Bobbili and Kanada kumali in its vicinity which can be potential sources for future earthquakes due to reactivation which is uncertain. These north-east and north-west trending faults are more vulnerable to reactivation with constant stress build-up. Apart from that, with a coastal belt of 1030 km, the state of Andhra Pradesh is also exposed to tsunami risk. During The Indian Ocean earthquake ( $M_w = 9.1$ , 2004) which lead to tsunami, tidal waves ranging from 2 to 6 m high reached the coast of Andhra Pradesh. A berth (WQ7) supported by an anchored sheet pile quay wall in Vishakhapatnam port failed immediately after the tsunami. Minor damages to structures have been observed all over the coastline and loss of life and livelihood has been reported. Few other earthquakes in Indian Ocean including the earthquakes of 2010 with magnitude 6.9 (Richter scale), 2012 with magnitude 8.2 ( $M_w$ ) and 2014 with magnitude 6.0 ( $M_w$ ) were felt by the people and caused a minor property damage without any casualties. Tsunami warning has been issued along the coast of Vishakhapatnam, Kochi, Bhubaneswar post 2012 earthquake. As there is no awareness on liquefaction phenomenon and related failures previously due to infrequent seismic events, there are no official records on failures but related displacements which can be related to liquefaction have been observed after the great Indian Ocean tsunami, 2004. The coastal shelves of Vishakhapatnam, ongole, Vijayanagaram are considered as weak zones where neotectonic activities have been established recently [22]. The tide gauge at Visakhapatnam port recorded tsunami of 1.4 m high [30]. According to Roy et al. [30], the first wave propagated around the Indian peninsula and has taken 2 h 18 min travel time to reach Visakhapatnam from the source. The study area has also experienced several seismic events of low to moderate magnitude ( $M_w$ ) greater than 6.0.

**Fig. 1** **a** Map showing the location of Vishakhapatnam in India. **b** Physical map of the study area. **c** Geological map and physical map of Vishakhapatnam city (Modified from Rao 2008)



**Geotechnical details**

Geotechnical data required in the current study have been collected from various private and government organizations for locations scattering all over the city. Red soils are found to be predominant in the study area followed by sandy soils in the next place. Few parts of the city near to port area and

coastal belt are covered with marine soils and soft clay sediments. SPT- N values ranges from 5 to 100 all over the city. Rock outcrop has been observed at few locations including Seethammadhara, Madhurawada, kailasagiri, Arilova. Few land-filled sites have been found across the city. The two-dimensional soil profiles along with groundwater table

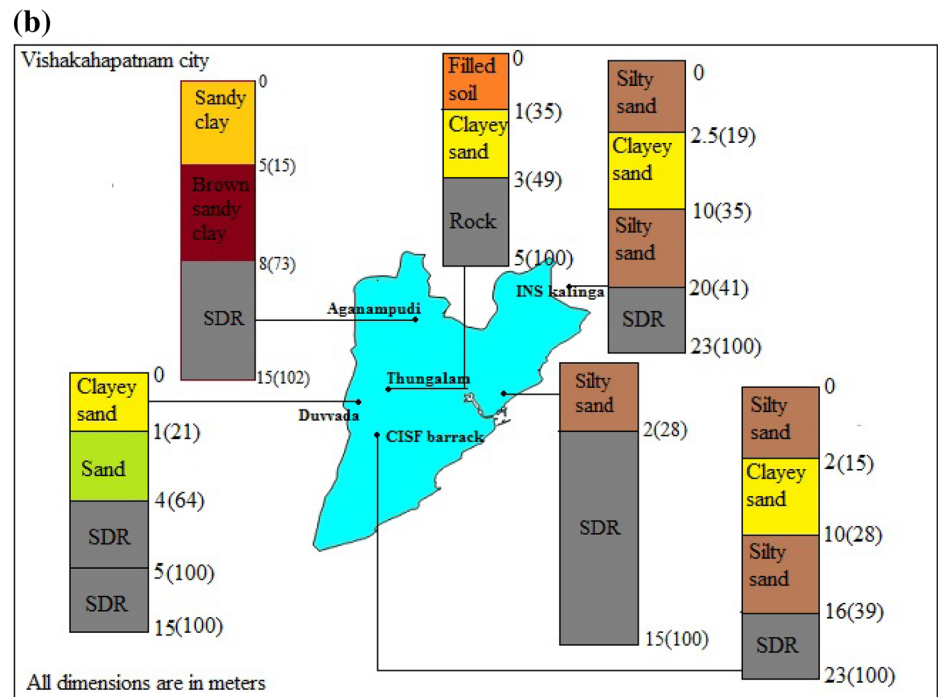
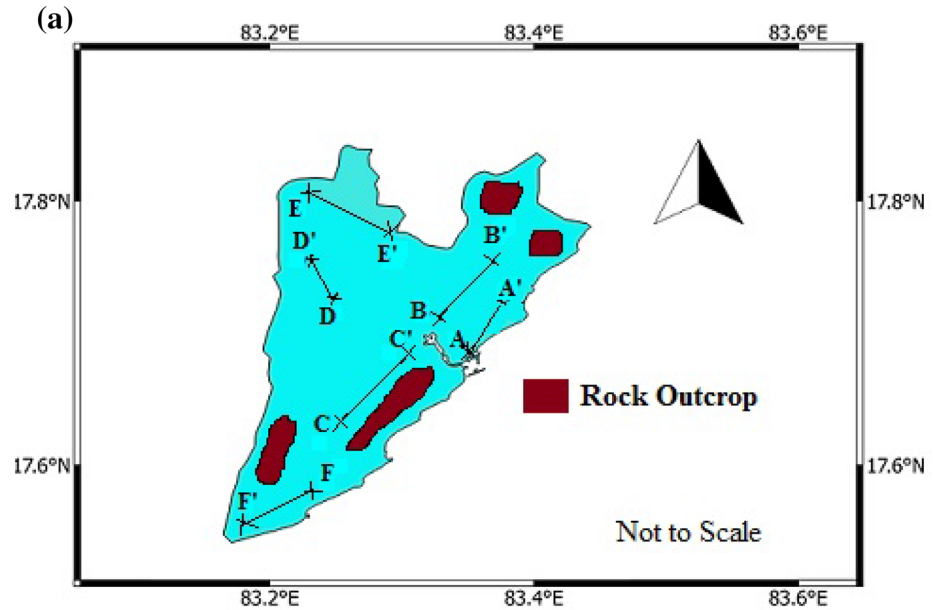
level, generated for few locations considered in the study are shown in Fig. 2.

### Equivalent linear ground response analysis

The intensity of Strong ground motion and local site conditions are the prominent parameters influencing damage caused to a structure. Dynamic behavior of the soil under seismic loading conditions can be better interpreted by

estimating the ground response and local site effects in a particular location. A seismic event is obviously associated with source rupture mechanism and seismic wave propagation through the underlying rock strata. At the end these seismic waves travel through different soil strata to the site of interest. The bedrock motion is prominently modified at the ground surface because of local soil layers above the underlying bedrock at a particular site of interest. The estimation of these amplifications or deamplifications in ground response due to local site effects is a convoluted problem

**Fig. 2** **a** Map showing the rock outcrop and soil profile cross-sections. **b** Borehole data shown for few locations of the study area. **c** 2-D Cross-sectional soil profiles in the study area



\* Corrected SPT-N (N<sub>c</sub>) values has been mentioned in parantheses

to the design engineers in populous cities where huge fraction of population may be affected due to devastating earthquakes. Therefore, one-dimensional ground response analysis has been carried out in the study area to evaluate the local site effects in modification of ground response using equivalent linear approach. Equivalent linear approach in 1-D ground response analysis has been used by many researchers from the past Yoshida et al. [41]; Phanikanth et al. [23]; Satyam and Towhata [24], as it gives better results at low strain levels. Theoretical approaches stand in need of sensitivity tests to be conducted at various sites and estimation and analysis of uncertainty is highly impractical [1]. One-dimensional wave propagation method is the widely used approach for estimation of ground response as it is rapid and simple with accurate results [32]. In this work, equivalent linear ground response analysis has been carried out, with the basic assumptions that the site is layered horizontally and single stiffness and damping values were utilized for all the frequency components using DEEPSOIL [44].

DEEPSOIL [13] is a computer program used for 1D ground response analysis. Equivalent linear approach has been used for layered soils to estimate the seismic response of horizontally layered soil deposits of the study area. This 1D site response analysis program can perform non-linear, equivalent linear and linear approach of analysis. The response analysis can be performed either in time domain or frequency domain. During high seismic intensities at bed rock level or/and high strain levels in the soil, an equivalent damping and soil stiffness for every soil layer cannot represent the behavior of entire soil column over the duration of an earthquake. In such cases also ground motion propagation through deep soil deposits can be simulated using this tool. The equivalent linear response analysis approximation used in DEEPSOIL is similar to the one used in SHAKE [32]. Any number of soil layers in the soil column and respective properties can be used and can choose between frequency independent and dependent formulations for shear modulus (Park et al. 2004).

For the response analysis, 64 locations throughout the city with a total of 209 boreholes were considered for the study. Bhuj earthquake (2001) ground motion of magnitude  $M_w = 7.7$ (Fig. 3) has been used for the analysis due to unavailability of recorded strong motion data in the study area.

The soil parameters required for the study were obtained from the bore hole exploration data obtained from different government and private organizations. The Solution for wave propagation is achieved using frequency domain analysis (FD) in equivalent linear approach. The equivalent linear approach is rapid and effective but is always a rough estimate of non-linear behavior of soils [14]. Soil properties of each soil layer are modeled using the damping versus shear strain curves and modulus reduction curves. Shear modulus reduction curves ( $G/G_{max}$ ) and damping ratio, both depending on

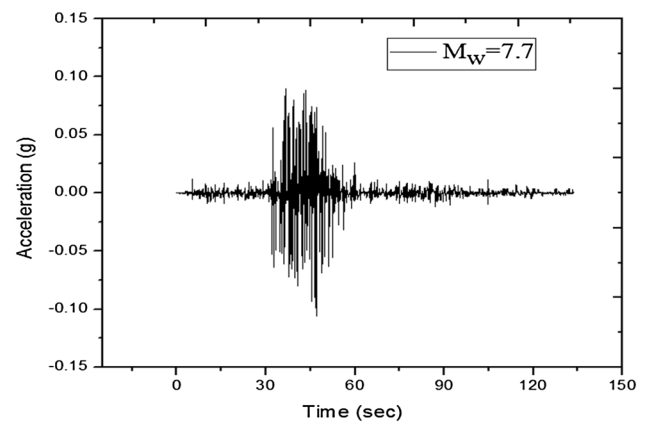


Fig. 3 Input ground motion data (Bhuj earthquake 2001)

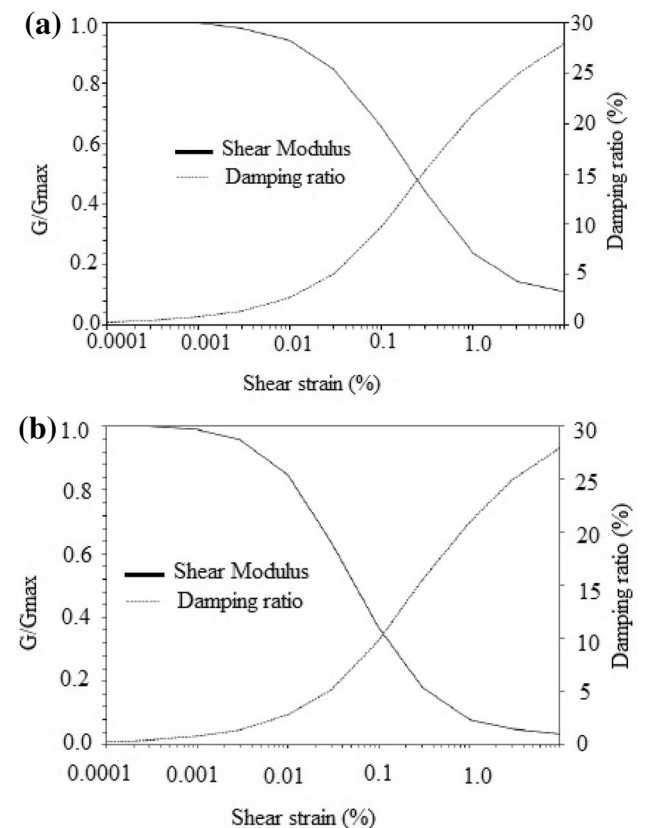


Fig. 4 a Modulus for clay [36] upper range and damping for clay [16]. b Modulus for sand [33] upper range and damping for sand [16]

the shear strain specified by Seed and Sun [36], Seed and Idriss [33] and Idriss [17] for clays and sands (Fig. 4a, b) have been used in defining the properties of the soil using discrete points. In DEEPSOIL [13], rock depth is assumed to be below the last layer of engineering bed rock ( $N > 100$ ). To prevent erroneous results the last layer was assumed to be the same up to a depth of 100 m.

From the past literature, it is evident that 5% damped elastic soil damping formulation in time Domain Site Response Analysis response spectra has shown a reliable match with the frequency domain solution. Therefore, fast Fourier transform was applied and analysis has been carried out for 5% damping ratio. PGA at surface and bedrock have been obtained from the ground response analysis. The Surface PGA values were identified to be in the range of 0.08–0.14 g. Site amplification factor is found to be in the range of 1.0–1.4.

Surface PGA values were used to identify different zones in the city with varying hazard. PGA (surface) map (Fig. 5.) has been prepared for the study area. It was observed that few locations in the city have shown higher response with ground accelerations in the range of 0.12–0.14 g and the site amplification factor has been observed to be increasing with increase in level of ground water table. PGA values found from the present study have been found to be in good match with the past studies conducted in the study area. Kumar et al. [20] conducted Probabilistic seismic hazard analysis for Vishakhapatnam and found the PGA to be 0.12 from the hazard curves developed for 10% rate of exceedance. Similar studies have been conducted by Sitharam et al. [37] in Bangalore which is also located in southern part of India (zone-II) and the PGA from deterministic and probabilistic seismic hazard analysis was found to be 0.121 g. Higher acceleration values of greater than 0.12 g has been observed in the locations including Pandurangapuram, Ganesh Nagar, pulagalipalem with water table at deeper depths of greater than 3–4 m. These locations have highly weathered rock, disintegrated rock, and a mixture of gravel, sand and pebbles as predominant soils. Comparatively lower response has been observed in locations with ground water table at shallow depths namely Sagarnagar, Siripuram, Tenneti Park and few areas near the port. A mixture of sand, silt and clay,

fine to medium sand are the prevailing soils found in these places.

These surface PGA values were further used to estimate cyclic stress ratio (CSR) in liquefaction hazard assessment for respective locations using stress based method.

## Liquefaction potential assessment

Devastating historic earthquakes that happened all over the world unfold that, the failure of soil due to liquefaction generally causes severe lifeline and structural damage in urban areas. Hence portraying the locations prone to liquefaction hazards is prominent for evaluation and reduction of seismic risk through appropriate method. Well established geologic and geotechnical data for an area helps in mapping of liquefaction susceptibility, as liquefaction mostly occurs in soils with low density and saturated granular sediments. The first and foremost simplified method for liquefaction hazard assessment has been proposed by Seed and Idriss [34] based on the concept of effective stress. Further, several methods have been introduced by various researchers based on effective stress and energy dissipation concepts. The Stress based method proposed by Boulanger and Idriss [6] and energy-based method proposed by Kokusho [19] have been used to evaluate the liquefaction hazard associated with the soils in the study area.

### Stress based method (Boulanger and Idriss [6])

Assessment of liquefaction potential of granular soils can be carried out by laboratory tests as well as observational data obtained from past major earthquakes. Foremost approach for estimating the liquefaction potential was developed by Seed and Idriss [34] method. Further, many stress-based approaches were proposed by various researchers i.e., seed and peacock [35], Iwasaki et al. [18], Youd and Idriss [43], Boulanger and Idriss [6], Andrus and Stokoe [3] and Robertson and Wride [29]. Boulanger and Idriss [6] have recommended a new methodology based on laboratory cyclic loading test results and comprehensive engineering judgment. The deformation behavior of fine-grained soils is grouped where soils within the sand-like behavior region are supposed to liquefy and have considerably lower Cyclic Resistance Ratio (CRR) values. Case histories have shown that clay mineral percentage is more relevant than percentage of clay size. So, Liquid Limit (LL) and plasticity index (PI) jointly give better indication than using clay content alone. Guo and Prakash [12] tested on silt–clay mixtures and found that at lower plasticity range, PI is inversely proportional to liquefaction resistance while PI is directly proportional to liquefaction resistant at higher plasticity range as in Fig. 6. The stress based approach developed by Boulanger and

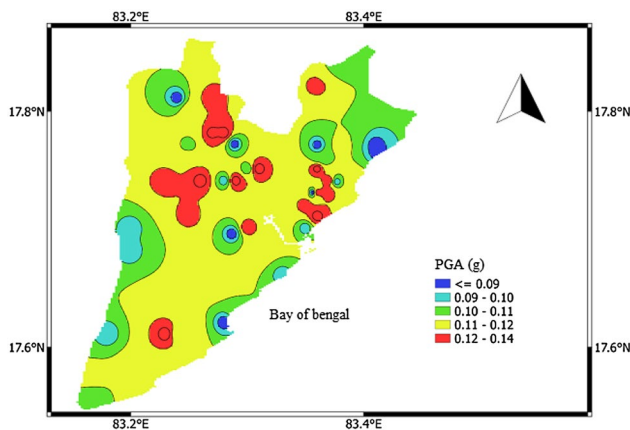
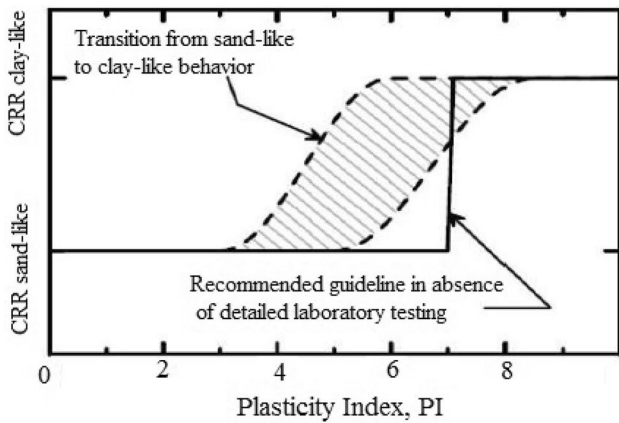


Fig. 5 SurfacePGA map (g) of Vishakhapatnam



**Fig. 6** Sand-like and clay-like sediment behavior differentiation criteria proposed by Boulanger and Idriss [6]

Idriss [6] for evaluating the induced stress is based on the effective stress principle has been evolved from investigations of numerous laboratory studies on the behavior of soils under cyclic loading and later by the confirmation supplemented with field case histories. Many researches across the globe has carried out liquefaction hazard assessment studies for various locations using different approaches selected depending on the geotechnical data availability, seismic history of the location and geology and geomorphology of the location [42]; Iwasaki et al. [18, 26]; Susumu [39]; Bird and Bommer [5]; Wakamatsu et al. [40]; Holzer [15]. In southern India, liquefaction hazard assessment studies have been carried out by Anbazhagan et al. [2] for Bangalore, Ganapathy and Rajawat [11] for Chennai and Satyam and Towhata [24] for Vijayawada. Apart from Bangalore, Chennai and Vijayawada assessment has been done for few other locations of south India with small sets of data available which doesn't account for complete assessment.

Hence in the present study to recognize the potential hazard imposed by liquefaction, a detailed assessment has been carried out to map the likelihood of liquefaction within Vishakhapatnam urban limits using SBM approach proposed by Boulanger and Idriss [6]. Geotechnical data required for the analysis has been collected from various organizations for 64 different locations throughout the city with a record of 209 boreholes. Bhuj earthquake motion has been taken as input ground motion for ground response analysis to determine site-specific PGA ( $a_{max}$ ) values (Table 1) as well as liquefaction hazard analysis.

From the available geotechnical data and the surface PGA values obtained through one-dimensional ground response using equivalent linear approach, likelihood of liquefaction at various locations throughout the city has been estimated using stress based. The stress imparted due to earthquake forces is represented by cyclic stress ratio (CSR) and the equivalent resistance offered by the soil column is termed

as cyclic resistance ratio (CRR). The onset behind every stress based method of liquefaction potential evaluation procedures are almost similar i.e., comparing cyclic resistance ratio (CRR) of the soil with seismically induced cyclic stress ratios (CSR) as explained in the first and for most method proposed by Seed and Idriss [34]. The flowchart for the procedure of liquefaction hazard assessment used in this research proposed by Boulanger and Idriss [6] has been shown in Fig. 7.

Liquefaction is likely when the cyclic stress ratio exceeds cyclic resistance ratio determined by corrected SPT N value. Soil profiles with corrected SPT N value, shear wave velocity and effective stress at different depths for few locations considered in the study are shown in Fig. 8.

Analysis of liquefaction hazard is attempted and it is observed that the liquefaction is certain in few regions of the city, i.e., MVP colony, lawsons bay colony, Thungalam, NTPC Simhadri, Yendada, Parawada, Akkayapalem and few locations in and around the port area. Locations in the central part of the city and northern part of the city has shown no signs of liquefaction with factor of safety against liquefaction ( $F.L > 2.0$ ) (Fig. 9.) namely Dwaraka nagar, INS Kalinga, Atchutapuram, RK beach, Pedda waltair. Many locations scattering all over the city has shown the probability of liquefaction to occur ( $F.L. = 1.0-2.0$ ) including Deepanjali Nagar, Seethammadhara, locations near R.K beach, Sheela nagar, Aganampudi, Old Municipal office area, INS Dega, Jagannadhapuram, Seethammadhara.

### Energy-based method [19]

Energy-based method of liquefaction potential is quite younger concept compared to stress based method. Conventional stress-based methods stand in need of selecting an equivalent number of cycles of load and equivalent uniform shear stress to resemble relevant seismic loading in the laboratory. Therefore, the concept of energy per unit soil volume could be an optimum solution to delineate the liquefaction potential of a soil deposit, extensively due to dynamic loading. Energy concept would replicate actual field conditions in an appropriate way, and any stress reversals resulting in dissipation of a particular amount of energy would be equivalent (in terms of pore pressure generated) to any other process resulting in the dissipation of same amount of energy [10]. The energy required to rearrange sand grains and the dissipated energy calculated from hysteresis loops were equated to [25] established the relationship among various parameters such as no. of cycles, shear stress, void ratio and pore water pressure. Efforts has been made to establish a proportional relationship between amount of energy dissipated per unit volume and pore water pressure by Davis and Berrill [8], Chapman et al. [7], Berrill and Davis [4], Law et al. [21], Figueroa et al. [10], Figueroa and Dahisaria

**Table 1** PGA at surface and bedrock for different locations in the study area

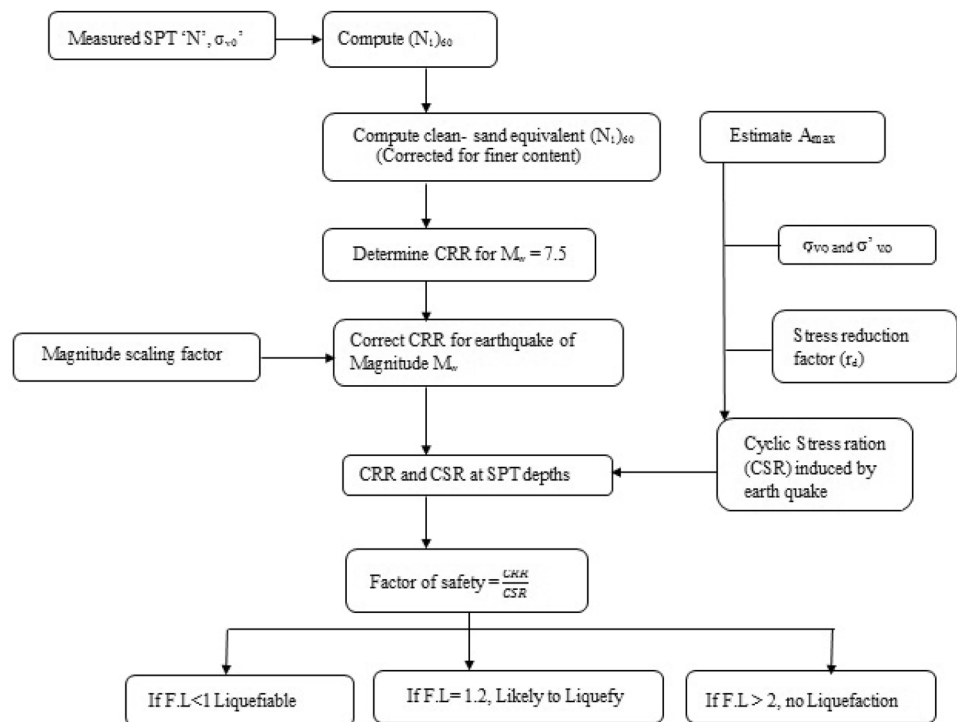
S. no.	Location	Latitude (°N)	Longitude (°E)	PGA <sub>Bedrock</sub> (g)	PGA <sub>Surface</sub> (g)
1	Tikkavani palem	17.59	83.12	0.1	0.12
2	Andhra University	17.74	83.31	0.11	0.13
3	Allipuram market	17.73	83.29	0.11	0.13
4	Panduranga puram	17.72	83.3	0.12	0.14
5	VSKP Railway station	17.73	83.27	0.1	0.12
6	Shipyards	17.7	83.26	0.1	0.12
7	HPCL	17.71	83.24	0.1	0.13
8	Ganesh Nagar	17.75	83.2	0.11	0.14
9	Murali nagar	17.76	83.25	0.11	0.14
10	Gopalapatnam (rural)	17.72	83.19	0.1	0.13
11	Ramakrishna Nagar	17.75	83.29	0.1	0.13
12	Padmanaba nagar	17.77	83.19	0.09	0.12
13	Narava	17.75	83.17	0.09	0.12
14	Durga nagar	17.749	83.169	0.1	0.13
15	Pendurthi Expressway	17.82	83.2	0.09	0.12
16	Pulagalipalem	17.82	83.21	0.1	0.13
17	East Point colony	17.74	83.33	0.09	0.12
18	madhav nagar	17.78	83.21	0.09	0.12
19	Sambuvanipalem	17.81	83.3	0.08	0.11
20	SBI steel plant	17.65	83.16	0.09	0.12
21	Santhi nagar	17.75	83.23	0.11	0.14
22	Sig nagar	17.78	83.32	0.09	0.12
23	Simhachalam	17.83	83.3	0.1	0.13
24	Simhapuri colony	17.79	83.22	0.13	0.14
25	Sinter plant	17.62	83.19	0.11	0.12
26	Marripalem	17.66	83.21	0.11	0.12
27	Steel plant	17.62	83.17	0.13	0.14
28	Adarsh nagar	17.75	83.33	0.11	0.12
29	Appikonda	17.59	83.17	0.1	0.11
30	Chinapalem	17.62	83.12	0.08	0.09
31	Madhavadhara Vuda colony	17.76	83.24	0.09	0.1
32	mamidilova	17.79	83.33	0.1	0.11
33	kalapaka	17.57	83.11	0.09	0.1
34	Gangavaram	17.64	83.23	0.1	0.11
35	Godduvanipalem	17.67	83.19	0.11	0.12
36	Dondaparti	17.74	83.29	0.11	0.12
37	Kommadhi	17.84	83.31	0.1	0.11
38	Children park, Mudhurasalova	17.77	83.3	0.09	0.1
39	Narsimha Nagar	17.75	83.29	0.1	0.11
40	Pedaghantyada	17.68	83.2	0.1	0.11
41	Vuda colony, gajuwaka	17.69	83.19	0.1	0.11
42	Peddamadaka	17.66	83.21	0.1	0.11
43	Pendurthi	17.81	83.19	0.11	0.12
44	Shivaji Park	17.69	83.15	0.09	0.1
45	MVP Sector-3	17.748	83.334	0.11	0.12
46	Airport	17.768	83.306	0.09	0.1
47	Rajayya peta	17.82	83.18	0.07	0.08
48	Relliveedhi	17.71	83.29	0.08	0.09
49	Aganampudi(near tollgate)	17.69	83.14	0.08	0.09
50	Arilova Ssector-II	17.78	83.3	0.07	0.08
51	Duvvada	17.71	83.14	0.08	0.09



**Table 1** (continued)

S. no.	Location	Latitude (°N)	Longitude (°E)	PGA <sub>Bedrock</sub> (g)	PGA <sub>Surface</sub> (g)
52	Gangavaram beach	17.63	83.22	0.07	0.08
53	Kapulauppada	17.85	83.32	0.09	0.1
54	NAD	17.75	83.22	0.07	0.09
55	NTR centre	17.78	83.35	0.06	0.08
56	Yaraada	17.67	83.27	0.07	0.09
57	Sriharipuram	17.705	83.227	0.06	0.08
58	Porlupalem	17.78	83.19	0.08	0.1
59	Seshadri nagar	17.79	83.19	0.08	0.1
60	Girijala	17.901	83.286	0.07	0.09
61	Siripuram	17.74	83.296	0.06	0.08
62	Srinivasa nagar	17.781	83.229	0.06	0.08
63	Isakathota	17.749	83.317	0.07	0.09
64	Tenneti park, Beach road	17.774	83.351	0.06	0.08

**Fig. 7** Flowchart for Stress based Method (Boulanger and Idriss [6])



[9] and kokusho [19]. The present study aims at identifying liquefiable sites throughout the city using EBM approach proposed by Kokusho [19]. The procedure adopted for the present study has been represented (Fig. 10) as a flowchart.

In the energy-based method, it is necessary to compare dissipated energy for liquefaction in soil layers with seismic wave energy during design earthquakes. To do this, the steps illustrated below are followed in the EBM procedure proposed by Kokusho [19].

- To estimate the liquefaction potential for soil profile at a particular location, the SPT  $N$  values available at each depth are normalized by the effective overburden stress  $\sigma'_v$  using the equation given below.

$$N_1 = 1.7N / (\sigma'_v / P_o + 0.7)$$

Where  $P_o$  is the atmospheric pressure generally taken as 98 kPa

- The Cyclic resistance ratio ( $R_L$ ) has been determined from a relation between  $R_L$  and normalized SPT  $N$  value ( $N_1$ ) and further effective confining stress ( $\Delta W / \sigma'_v$ ) has

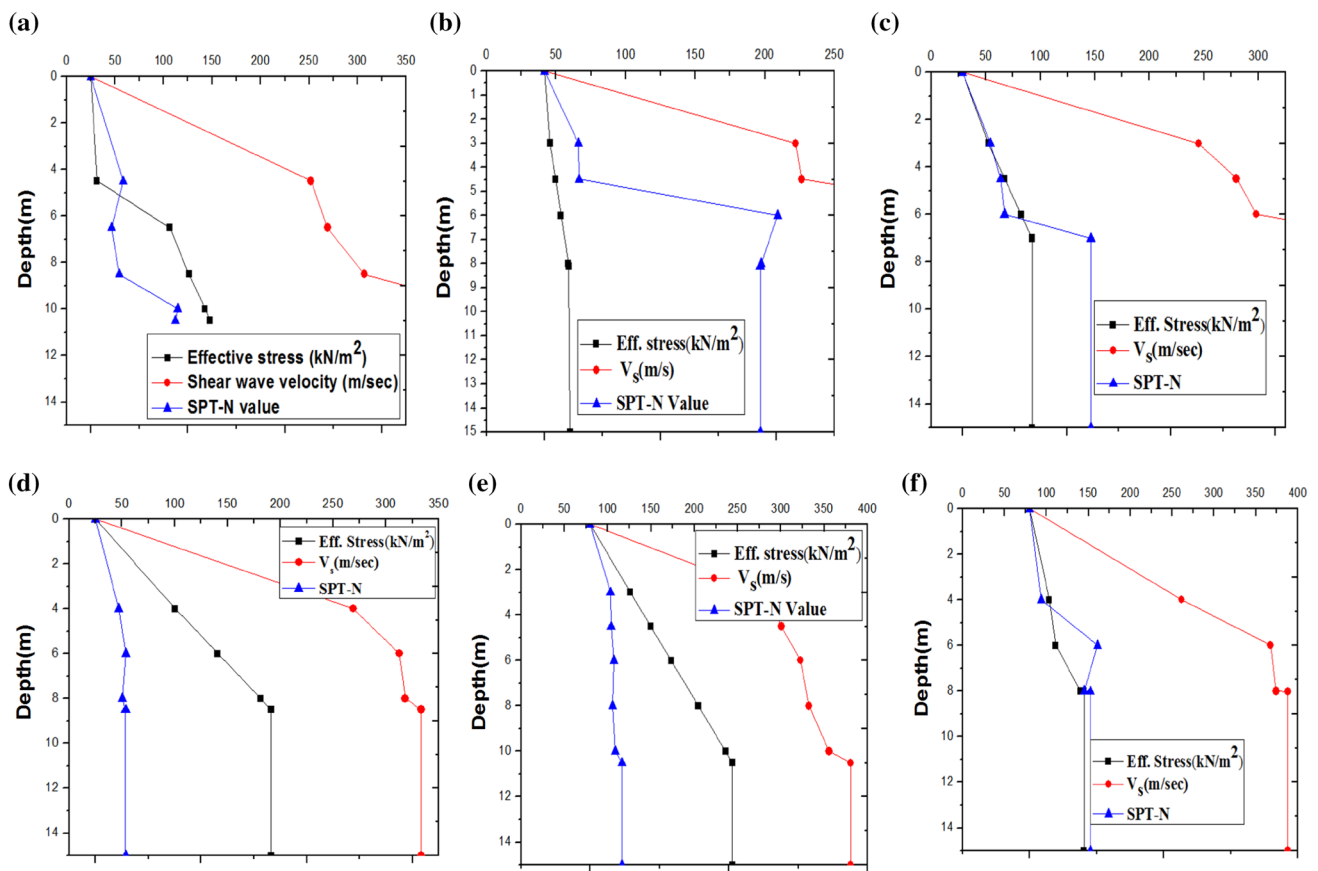


Fig. 8 SPT-N, shear wave velocity, effective stress profiles for a Port Area, b Jagannadhapuram, c Waltair, d INS Kalinga, e Siripuram, f RK Beach

been estimated at each depth. The correlation between  $R_L$  and  $\Delta W/\sigma'_c$  used in this work has been proposed from numerous tests on sands with variable relative densities

and fines contents irrespective of the number of load cycles  $N_C$  [19].

- The dissipated energy normalized by effective confining stress  $W/\sigma'_c$  for a soil specimen to liquefy is uniquely correlated with normalized strain energy  $W/\sigma'_c$  imposed as shown in (Fig. 11) by series of triaxial tests for sands with various density and fines content, though almost the same correlation also holds in torsional shear tests for harmonic and irregular cyclic loading. The correlation may be approximated as

$$W/\sigma'_c = 5.4 * 10^{1.25 \log (\Delta W/\sigma'_c)}$$

- The energy capacity at a soil layer of thickness  $H$  to liquefy, i.e.,  $WH$  has been arrived at using average mean effective stress estimated at a layer and the upward energy is calculated from the one-dimensional equivalent linear ground response analysis using the relation between energy, particle velocity and seismic impedance.
- The cumulative of the ratio of energy capacity for the liquefaction ( $WH$ ) and the upward energy gives Accumu-

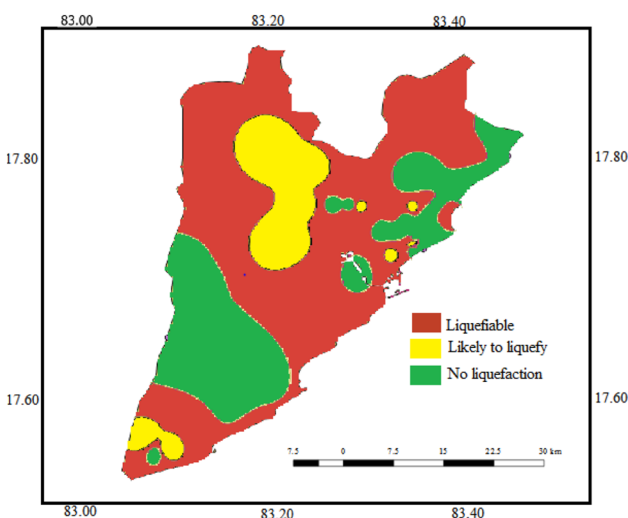


Fig. 9 Liquefaction hazard map Using SBM approach [6]

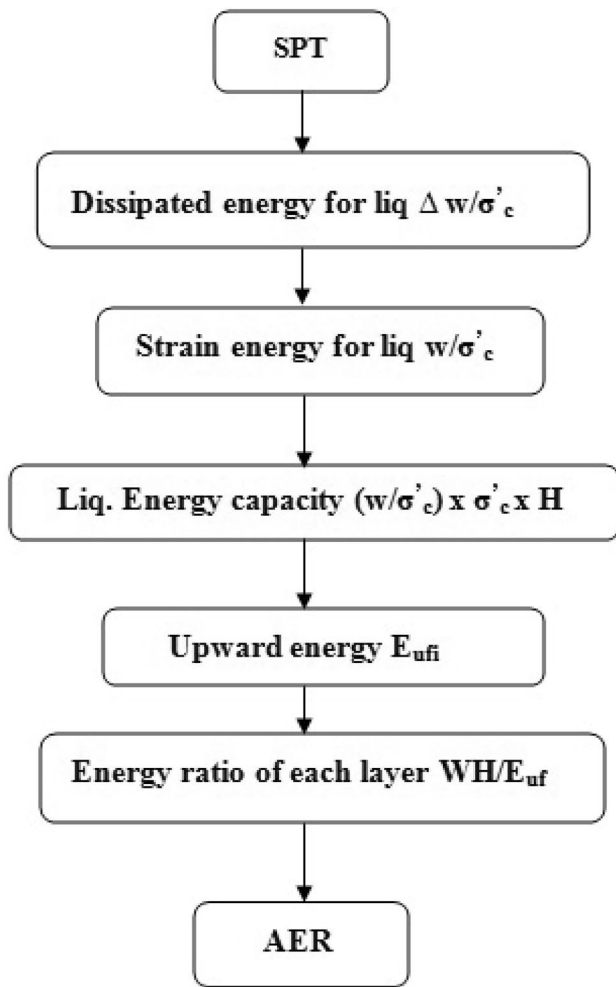


Fig. 10 Liquefaction hazard assessment methodology using EBM approach (Kokusho [19])

lated Energy Ratio (AER) which should be greater than 1.0 to conclude that the soil is not prone to liquefaction.

Energy ratio and accumulated energy ratio at each layer in the soil profile has been calculated for all the locations with available geotechnical data using the above-mentioned procedure of energy approach as shown in Fig. 12 and factor of safety against liquefaction has been estimated. From the results of EBM approach, it has been observed that most of the locations with silty sand and fine sand along the coast line and throughout the city are likely to be liquefiable, whereas southern part of the city is suggested to be certainly liquefiable from the results of SBM approach. Liquefaction hazard map has been generated from the results of EBM approach to identify the liquefiable sites, shown in Fig. 13.

The results can be used in identifying sand deposits likely to undergo liquefaction. These results though does not provide reliable match between the hazard maps generated using two methods, it is suggested that most of the locations

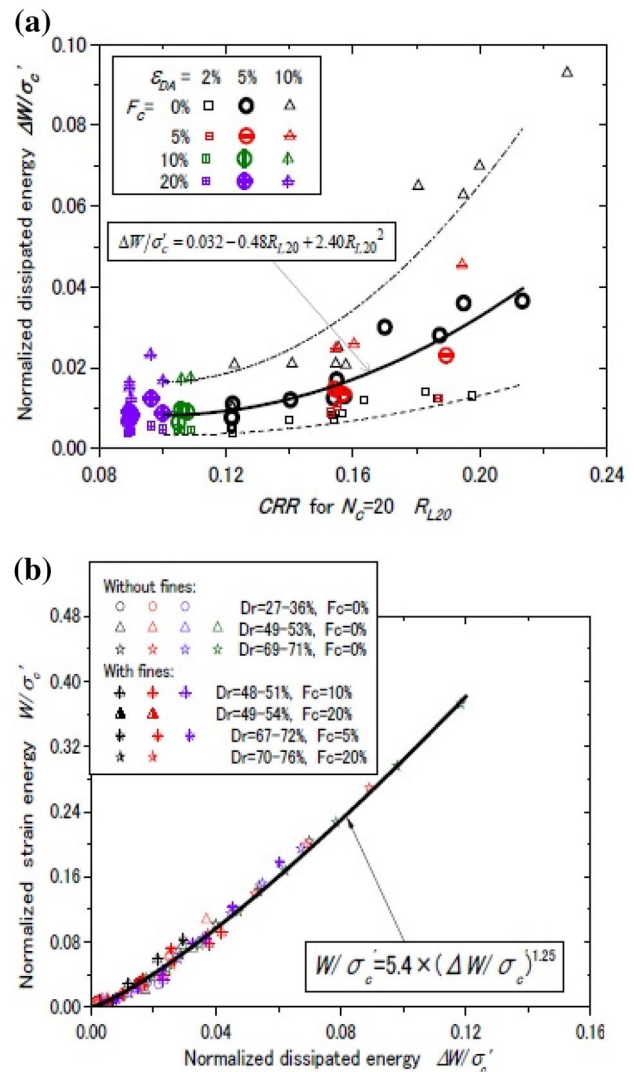
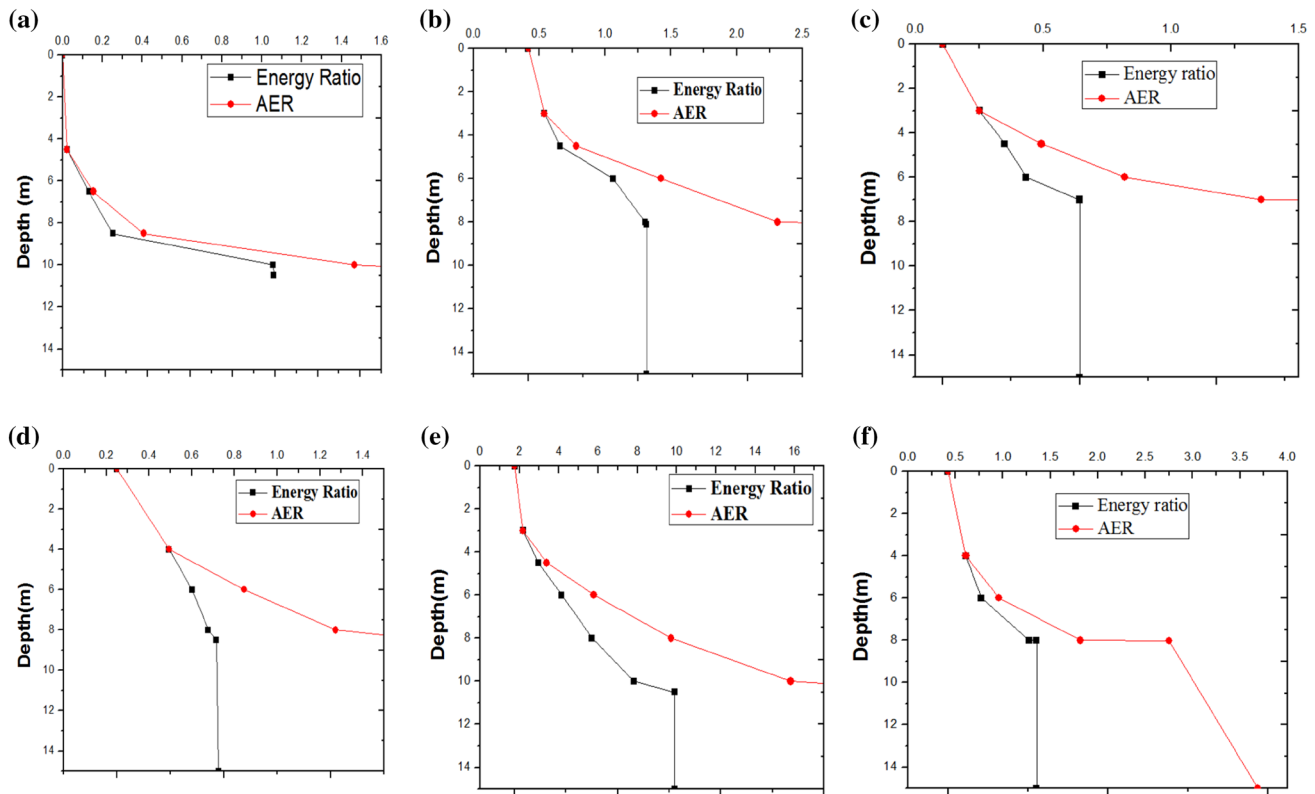


Fig. 11 a Dissipated energy  $\Delta W/\sigma'_c$  versus CRR for  $N_c = 20$  [19]. b Normalized strain energy versus dissipated energy  $W/\sigma'_c$  [19]

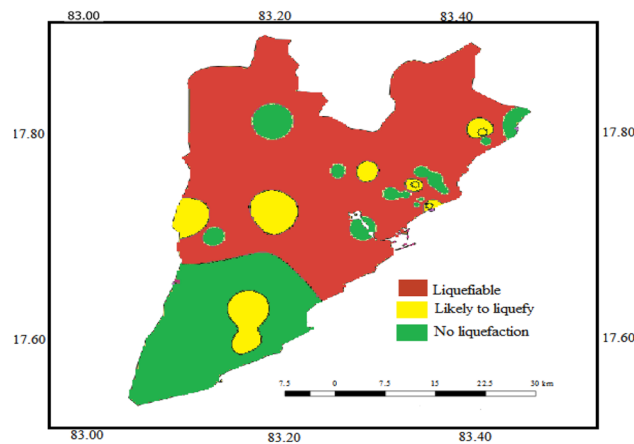
in the city are prone to liquefaction. The locations with rock out crops and stiff clays such as Madhurawada, Yendada, Waltair and Kapparada has shown no chance of liquefaction. It is suggested to use any of the two methods based on the intensity of input strong motion, availability of geotechnical and geological data and other required input parameters.

### Discussions

Past damages due to liquefaction of saturated soils have shown that the ground failed and sand boils have occurred leading the structure to subside unevenly resulting in cracking, tilting, or even collapse. Major earthquakes, such as the 1906 San Francisco, 1964 Alaska, 1964 Niigata-Japan, 1989 Loma Prieta, 1995 Kobe-Japan, 1999 Chi-Chi, Taiwan and



**Fig. 12** Energy ratio ( $WH/E_{uf}$ ) and Accumulated energy ratio(AER) profile for locations **a** Port area, **b** Jagannadhapuram, **c** Waltair, **d** INS Kalinga (Bheemunipatnam), **e** Siripuram, **f** R. K. Beach



**Fig. 13** Liquefaction hazard map using EBM approach [19]

2001 Bhuj, India resulted in devastating ground damage due to liquefaction and therefore explained the need for engineering approaches to estimate and mitigate the liquefaction hazard [31]. Since 1964, experimental and analytical studies have been carried out to better understand this phenomenon.

Ground response analysis in the study area suggests that the city is prone to higher acceleration than the peak

acceleration specified by IS: 1893-2002. And it is observed that the local site conditions such as groundwater level and density of the soil have their own impact on the response. Using the collected SPT N data detailed liquefaction hazard assessment using both SBM and EBM approaches (Table 2) has been attempted and it is observed that the liquefaction is certain in few places of the city, i.e., MVP colony, lawsons bay colony, Thungalam, NTPC Simhadri, Yendada, Parawada, Akkayapalem and few areas in the port, etc. From the results of SBM and EBM, it is observed that locations in southern part of the city have shown no signs of liquefaction with factor of safety against liquefaction ( $F.L > 2.0$ ). Liquefaction is certain ( $F.L < 1.0$ ) in locations of northern and central parts of the city. Many locations scattering all over the city has shown the probability of liquefaction to occur ( $F.L. = 1.0-2.0$ ) i.e., Deepanjali Nagar, Seethammadhara, R.K beach, Sheela nagar, Aganampudi, Old Municipal office area and few locations in the port etc. EBM approach suggest few sites to be certainly liquefiable in contrast to SBM approach which suggests the same locations are to be likely to liquefy or having no chance of liquefaction.

**Table 2** Liquefaction analysis using SBM and EBM for locations (a) Port Area, (b) Auto Nagar (c) INS Kalinga

Depth (m)	SBM			EBM			
	CSR	CRR	$F_L$	WH(kN/m <sup>2</sup> )	$E_{uf,ds}$ (kN/m <sup>2</sup> )	WH/ $E_{uf}$ (%)	AER
0	0.067	0.026	0.387	14.541	697.399	0.021	0.021
4.05	0.083	0.094	1.131	39.084	313.652	0.125	0.145
7	0.089	0.152	1.712	84.896	358.438	0.237	0.382
10	0.091	0.026	0.288	412.080	415.877	0.991	1.373
15	0.09	0.583	6.462	137.773	138.626	0.994	2.367
0	0.070	0.098	1.398	176.291	732.431	0.241	0.241
3	0.092	0.171	1.866	110.000	387.910	0.284	0.524
4.5	0.089	0.082	0.923	189.118	498.191	0.380	0.904
6	0.094	0.552	5.879	306.013	682.654	0.448	1.352
8	0.096	0.703	7.323	469.258	801.422	0.586	1.938
10	0.099	0.703	7.119	138.091	214.897	0.643	2.580
4	0.07	0.25	3.53	258.29	1060.00	0.24	0.24
6	0.07	0.32	4.64	235.46	669.78	0.35	0.60
8	0.07	0.42	6.25	291.49	682.65	0.43	1.02
12	0.07	0.54	8.10	83.56	179.60	0.47	1.49

### Conclusions

Higher ground acceleration values have been observed at locations where groundwater table is at shallow depths along with the presence of silt and sandy soils. From stress based and energy based methods of liquefaction assessment, it is evident that most of the locations scattering all over the city have a chance of liquefaction depending on the intensity of the ground motion and local site conditions such as few sectors of MVP colony, Atchutapuram SEZ sites, Gajuwaka. The results from EBM approach when compared with that of SBM approach has not shown a reliable match because of the uniqueness in the concept and delineated procedures. EBM method can be employed as a cross-check to SBM in challenges where the engineers are not confident about the liquefaction potential of the soils subjected to exceptional magnitudes of seismic events. Among the two methods, the hazard map from SBM approach is suggested to be used as it is found to be reliable in terms of economy and feasibility to use by the practitioners from the present study.

The findings from the current research will be of great use in identifying the sites with higher ground accelerations and design the structure accordingly. PGA values will be used as input in earthquake-resistant designing of infrastructure. Locations with possible liquefaction risk can be picked from the hazard maps generated and mitigation measures can be suggested based on parameters such as type of the structure proposed to be constructed in the site, availability of stabilizing materials and various other local conditions. Hence the hazard maps from the present study will be supportive in future infrastructure development, planning, design, analysis and construction of structures with reduction in seismic risk.

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