Bulletin of Engineering Geology and the Environment (2020) 79:1721–1733
https://doi.org/10.1007/s10064-019-01644-6

ORIGINAL PAPER

Multi criteria study for seismic hazard assessment of UNESCO world heritage Ahmedabad City, Gujarat, Western India

Vinay Kumar Dwivedi[1] · R. K. Dubey[2] · Vasu Pancholi[1] · Madan Mohan Rout[1] · Pawan Singh[1] · B. Sairam[1] · Sumer Chopra[1] · B. K. Rastogi[1]

Received: 14 May 2019 / Accepted: 16 October 2019 / Published online: 26 November 2019

Abstract

Ahmedabad, the most populous city of Gujarat, assigned zone III in the seismic zone map of India (BIS 2002), has experienced moderate earthquakes in the past. Several high-rise buildings were collapsed or severely damaged in the city during 2001 Bhuj earthquake (Mw 7.6), which was 240 km from the city. Keeping this in view, micro-level seismic hazard assessment in the city is carried out using geotechnical, geological, and geophysical inputs, which may help in designing buildings and other civil engineering structures and will reduce the probability of loss of life and property in this region. A total of 23 boreholes (11 boreholes of 80 m, 7 boreholes of 40 m and 5 boreholes of 35 m) were drilled at the different locations in the city. To estimate the shear-wave velocity, we have employed direct and indirect methods. PS logging is carried out in 11 boreholes, and shallow geophysical investigation (multi-channel analysis of surface waves, MASW) is carried out at 54 sites. The field and laboratory tests on soil samples, geophysical investigations, and seismotectonic information enabled us to estimate soil overburden thickness, shear-wave velocity, factor of safety against liquefaction, and site response in terms of amplification factor. The peak ground acceleration was estimated at engineering bed rock level (Vs 760 m/s) by PSHA. All this information is used in preparing an integrated seismic hazard (SH) map of the Ahmedabad City using analytical hierarchal process. The seismic hazard map is characterized into three broad categories: low, moderate, and high. The western part of the Ahmedabad shows the highest hazard. The northern and the eastern parts show moderate seismic hazard. It is observed that the presence of sand and flood plain deposits along the Sabarmati river increases the hazard. The study has also highlighted that the presence of a paleochannel increases the overall hazard, which is clearly visible in integrated hazard map.

Keyword Seismic hazard assessment · Analytical hierarchy process · Geographic information system

Introduction

Seismic hazard assessment (SHA) of cities that have experienced exponential growth in the last 2–3 decades is important. The regional hazard zonation do not incorporate local effects leading to its infeasibility (impracticable) in land use development and planning, hazard mitigation and management, and structural engineering applications in site-specific terms. It is necessary to overcome these limitations, especially in the highly populated urban centers with unplanned urbanization

✉ Vinay Kumar Dwivedi
vinay_geologist@rediffmail.com

R. K. Dubey
rkdubey1085@hotmail.com

Vasu Pancholi
vasupancholi@gmail.com

Madan Mohan Rout
madanmohanrout@gmail.com

Pawan Singh
pawansinghrajawat4@gmail.com

B. Sairam
sairam.b78@gmail.com

Sumer Chopra
sumer.isr@yahoo.com

B. K. Rastogi
bkrastogi12@gmail.com

1 Institute of Seismological Research, Raisan, Gandhinagar, Gujarat 382009, India

2 Indian Institute of Technology, Indian School of Mines IIT (ISM), Dhanbad, India

practices. A quasi-deterministic or quasi-probabilistic approach employs a hybrid seismological, geological, geomorphological, and geo-technically guided framework in which all the potential hazard attributing features are considered with relative rankings in a logic tree, fuzzy set, or hierarchical concept (Nath et al. 2005). Seismic microzonation divides a region into sub-regions in which different safeguards must be applied to reduce, and prevent damages, loss of life, and societal disruptions, in case a large devastating earthquake strikes the region. It involves prediction of the hazard at different scales (say, from 1:50,000 to 1:25,000, 1:10,000, or 1:5,000 scales) (Nath et al. 2009). All geological, geotechnical, and seismological attributes are assessed to deliver the seismic microzonation in terms of a hazard index map. A microzonation project can be of different levels based on the mapping resolution, precision, data volume, and complexity of the problem (Bard et al. 1995).

The hazard during an earthquake is significantly controlled by geotechnical material properties. The site-specific attributes related to surface geologic conditions may affect the level of strong ground motions (Aki 1988; Field et al. 1992; Nath et al. 2000; Sitharam and Anbazhagan 2008). It is, therefore, important to estimate appropriate site-specific design ground motions for earthquake-resistant structural design and the hazard assessment. Since, multiple hazard components are involved, a robust decision support tool for hazard classification shall include every component and their likely contribution to the overall hazard. To that effect, seismic microzonation is carried out taking into account multiple criteria that accounts for several factors such as site response, shear-wave velocity, seismotectonics, landslide, geomorphological features, liquefaction assessment besides the strong ground motions (Sitharam and Anbazhagan 2008; Pal et al. 2008; Nath et al. 2008). After 2001 Bhuj earthquake, several studies related to the seismic hazard were carried out in different parts of the Gujarat (Singh et al. 2003; Iyengar and Raghukanth 2004; Yadav et al. 2008; Chopra et al. 2010, 2012, 2013). The city of Ahmedabad has experienced an intensity of VII on MSK-64 scale during 2001 Bhuj earthquake (Pande and Kayal 2003) and for which Iyengar and Raghukanth (2004) has estimated PGA of 0.15 g. Singh et al. (2003) and Chopra et al. (2010) have also estimated the strong ground motions due to 2001 Bhuj earthquake at various sites in Gujarat. Yadav et al. (2008) studied the probability of earthquake occurrence in three regions of Gujarat based on stochastic models at different time intervals. Chopra et al. (2012, 2013) carried out the deterministic seismic hazard assessment and estimated the earthquake strong ground motions for the entire Gujarat region at bedrock level and surface using stochastic finite-fault modeling.

The 2001 Mw 7.7 Bhuj earthquake was one of the most destructive earthquakes in India that killed around 14,000 people (EERI 2002). The damage was spread over a radius of 400 km including major cities of Ahmedabad, Bhavnagar, and Surat located at distances of more than 250 km. In these cities, many multistory buildings were collapsed. The site amplification is attributed to be one of the contributory factors for damages at far off distances. In Ahmedabad alone, 130 reinforced concrete frame buildings were either collapsed or seriously damaged (Goel 2001; EERI 2002; Murty et al. 2002). The Ahmedabad City is mushroomed on either side of the Sabarmati River, which flows from NE to SW. The area is characterized by more or less flat land topography with the major contours of 60, 40, and 20 m occupied by the sediments of Sabarmati River and Aeolian sands which were subsequently oxidized and pedogenized and the Aeolian sand imparts low height undulating topography. Numerous gullies and ravines are observed along Sabarmati bank on the northern side, while the depositional terraces were reported by GSI on the southern bank.

The study area lies in zone III (BIS 2002) where damaging earthquakes of magnitude up to 6 are expected. There is distance of over 240 km from Kachchh. To minimize the loss of life, property damage, social, and economic disruption caused by the earthquakes, it is essential that reliable estimates of seismic hazard should be available. The Ahmedabad is located on soft sediments of the Sabarmati river basin that are prone to amplification. This the India's first heritage city declared by UNESCO.

In this work, geotechnical investigations are carried out in 23 boreholes, PS logging in 11 boreholes and multichannel analysis of surface wave at 54 sites in the Ahmedabad City. We have estimated the shear-wave velocity both by direct and indirect measurement. These investigations provided the distribution of shear-wave velocity in the city. This information is useful for estimating liquefaction potential and obtaining level of strong ground motions at the surface. The ground motion at the engineering bedrock (Vs 760 m/s) is estimated by PSHA analysis for 2% PE in 50 years, which corresponds to maximum credible earthquake (MCE). The pair-wise comparison of different attributes like shear-wave velocity, acceleration, liquefaction potential, and surface geology obtained from geotechnical and geophysical investigations is performed using AHP (Saaty 1987) to get an integrated seismic hazard map for Ahmedabad by giving suitable weightages and ranks to the attributes. Since the city is traversed by a major river that divides the city into two parts, the role of paleochannel in modifying the hazard is also investigated in the integrated hazard map of the Ahmedabad City.

Geological, geomorphological, and seismotectonic set up of the study area

Ahmedabad is one of the largest growing city of India founded in the 15th century with a population of around 6.2 million (Census 2011). It has an average elevation of 53 m from the mean sea level (MSL). It is situated on thick continental quaternary sequences of Sabarmati River basin (Tandon et al. 1997). The Ahmedabad City falls within the NNW-SSE–oriented Cambay rift basin bounded by east marginal and west marginal faults. These faults are dissected by many transverse faults (Wani and Kundu 1995). The quaternary deposits are about 300-m thick (Merh 1995). The alluvium mainly consists of alternate layers of fine to coarse grained sand, gravel, and clay. The alluvium is underlain by more than 3000-m thick tertiary sediments deposited over Deccan traps (Kaila et al. 1990). The quaternary succession of the Sabarmati basin consists of conglomerate, sandy, and silty soils and divided into four stratigraphic subdivisions viz. Waghpur Formation, Sabarmati Formation, Mahesana Formation, and Akhaj Formation (Tandon et al. 1997). The Waghpur Formation is characterized by well sorted fine buff sand, while the Sabarmati Formation is the youngest formation and consists of unconsolidated alluvium derived from Aravalli mountains (Sareen et al. 1993; Tandon et al. 1997).

Geomorphologically, the study area can be divided into residential upland, low land, dune, and interdunal regions with few water reservoirs or ponds (Fig. 1). The low land regions are further classified into flood plain, bad land, terrace, point bar, channel bar, and recent channel. The Sabarmati river flows through the middle of the Ahmedabad City (Fig. 1), which dries up in summer leaving only a small stream of water. Topographically, the study area is almost flat in nature except few small hills of Thaltej-Jodhpur Tekra. The average annual rainfall in the study area is 635 mm.

The region is moderately active, seismically, and not much seismicity is observed in and around Ahmedabad City. A catalogue of earthquakes (Table 1) is prepared by ISR (2016-2017), and the historical seismicity map of the Ahmedabad City and surroundings is prepared (Fig. 2). Eight earthquakes of magnitude varying between 2.7 and 5.7 are observed within 80-km radius of Ahmedabad (Table 1). In the historical past, Ahmedabad experienced four earthquakes of magnitudes 4.6, 3.7, 5.7, and 3.7 in 1840, 1843, 1864, and 1897 respectively. Five other small shocks are cataloged. Moreover, a large earthquake in Kachchh region (M > 7) can affect high rise buildings in Ahmedabad City.

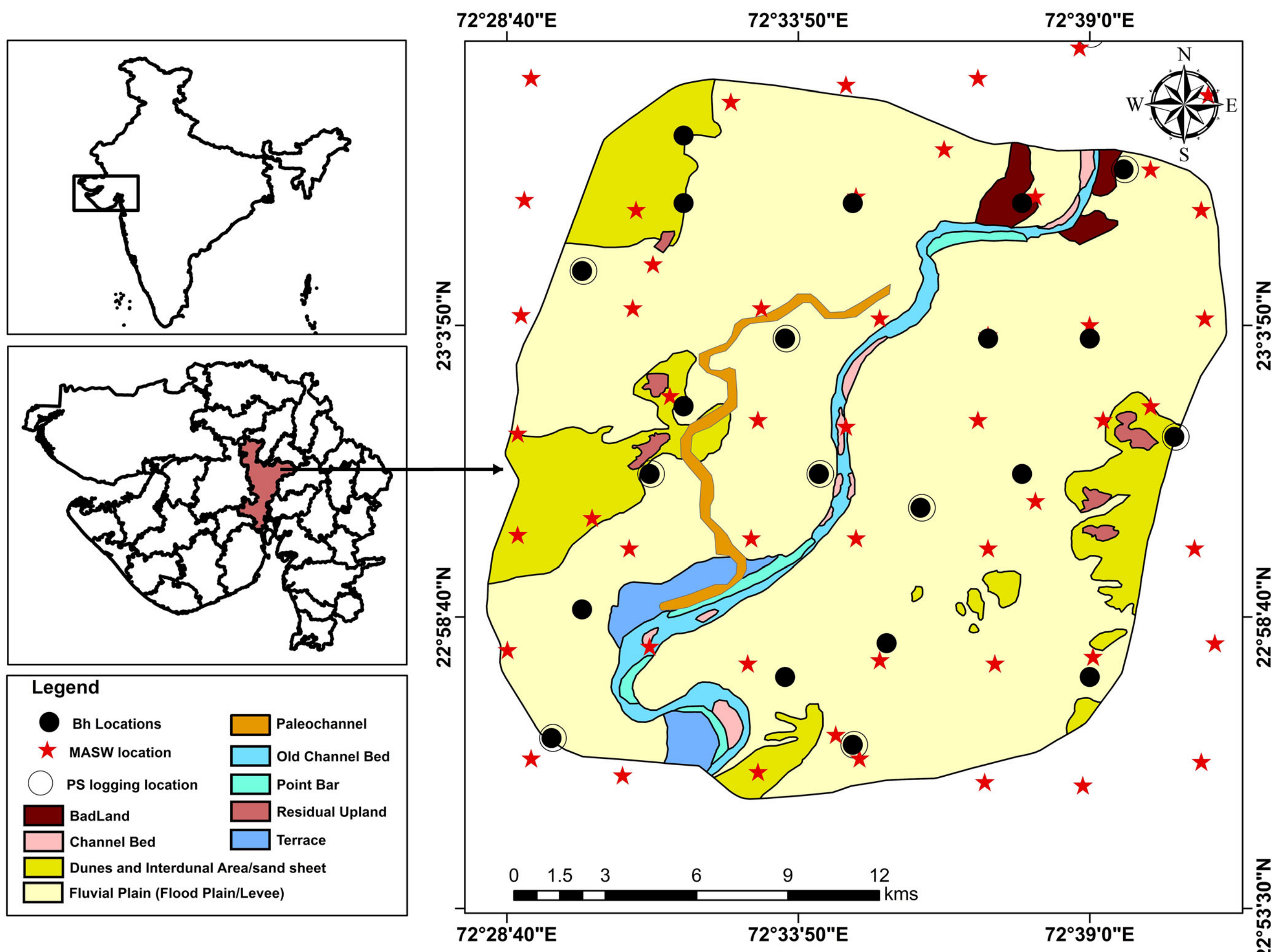

Fig. 1 showing Borehole, PS logging, and MASW locations with geological and geomorphological setup of the study area

Table 1 Catalog of earthquakes during 1840 to 2016

Longitude	Latitude	Year	Mag	References
72.67	23.05	1840	4.6	USGS
72.7	23	1843	3.7	OLD
72.8	22.3	1864	5.7	CHAN
72.7	23	1897	3.7	OLD
72.67	23.05	1898	4.3	USGS
72.14	22.87	1980	3.1	GERI
72.19	22.07	1982	2.9	GERI
72.777	23.513	2007	2.4	ISR
72.174	22.444	2007	1.8	ISR
72.084	22.98	2009	1.6	ISR
72.082	23.448	2009	1.4	ISR
72.417	22.703	2009	1.6	ISR
71.897	22.306	2009	1.4	ISR
72.842	23.324	2010	2.5	ISR
72.474	22.655	2011	1.2	ISR
72.47	22.65	2011	1.5	ISR
72.68	23.08	2012	1.9	ISR
71.924	22.513	2012	1.4	ISR
72.092	22.799	2012	1.6	ISR
72.634	23.028	2013	2.3	ISR
72.971	23.244	2014	2.5	ISR
72.014	23.234	2014	2.6	ISR
71.979	23.078	2014	3.7	ISR
71.951	22.512	2014	2.1	ISR
72.125	22.749	2016	1.7	ISR

Geotechnical investigations

A total of 23 boreholes (11 boreholes of 80 m, 7 boreholes of 40 m, and 5 boreholes of 35 m) were drilled at different locations in the city (Fig. 1). The boreholes are located at 2.5 km interval. During boring, soil samples (both disturbed and undisturbed) were collected for field and lab analysis to find out index properties of soil. The standard penetration tests were conducted, as per IS-code, at a depth interval of 3 m in every borehole. The SPT-N blow count and lithology were recorded during the sampling in the field and index properties of the disturbed and undisturbed samples of the soils, like grainsize analysis, Atterberg test, density, specific gravity was obtained and used for the seismic hazard assessment (Cavallaro et al. 2016). More than one thousand samples were collected (Dwivedi et al. 2017) and used for the seismic hazard assessment. The lithology of the study area generally varies from silty sand to clayey sand. The information pertaining to the depth of the water table is also collected during drilling. The ground water level of the study area is quite variable ranging from 3 to 50 m. These variations in water level may also be due to drilling of boreholes during different season. The SPT-N values measured in the field are generally low at shallower depths. The blow counts greater than 50 are generally encountered at depths of 6 to 9 m.

Geophysical investigations

For the estimation of V_P and V_S, the suspension PS logging test was carried out in 11 boreholes with depths ranging from 60 to 80 m. The suspension PS logging is relatively recent technology in geotechnical engineering and engineering geophysics. It is one of the best methods for the estimation of high resolution 1D V_P and V_S profiles in a single borehole at depths up to 80 m or even greater which are used for assessment of site characterization. It offers very high resolution (typically 1 m) data for resolving thin layers. The maximum measurable depth depends upon the maximum depth of open space available in a borehole. Generally, borehole collapse or mud filling at the bottom of the hole restricts depth of the Vs measurements. The suspension PS Logger probe is about 8.0-m long, comprises of a weight, source driver, source, filter tube, lower and upper geophone, head reducer, cable head, 4-conductor cable, winch, and logger/recorder (Sairam et al. 2018). Also, multichannel analysis of surface wave (MASW) is carried out at 54 sites covering the entire city. This technique utilizes the dispersive properties of Rayleigh waves for the estimation of a V_S profile of the subsurface (Caruso et al. 2016). The entire process of MASW consists of three major steps, namely acquisition of multichannel seismic data, generation of the dispersion curve, and estimation of the VS profile. The recommendation of Park et al. (1999) is followed to obtain a laterally continuous 2D V_S profile. A 48-channel engineering seismograph was used to acquire the data. The data were acquired using the standard CMP roll-along technique to achieve a continuous shot gather. A 30-kg weight is dropped on a metal plate to generate seismic waves. These waves were recorded on 24 vertical-component 4.5 Hz geophones/receivers planted at every 2-m interval along the profile, which responded to frequencies from 1 to 90 Hz in a 24-channel seismic shot gather. The acquisition parameters of the geometry are selected to optimize the imaging of subsurface layers down to more than 30 m depth. The signal-to-noise ratio of the processed data is more than 85 at each site. In the dispersion curve, the analyzed frequency was in the range 4–50 Hz. Each dispersion curve was individually inverted to obtain a V_S profile by setting the initial model and performing a least-squares minimization (Xia et al. 1999) using SurfSeis (Kansas Geological Survey [KGS] 2010).

Attributes for hazard analysis

Site characterization

It is necessary to understand the subsurface lithology of on area to estimate the effect of earthquake at a site of interest.

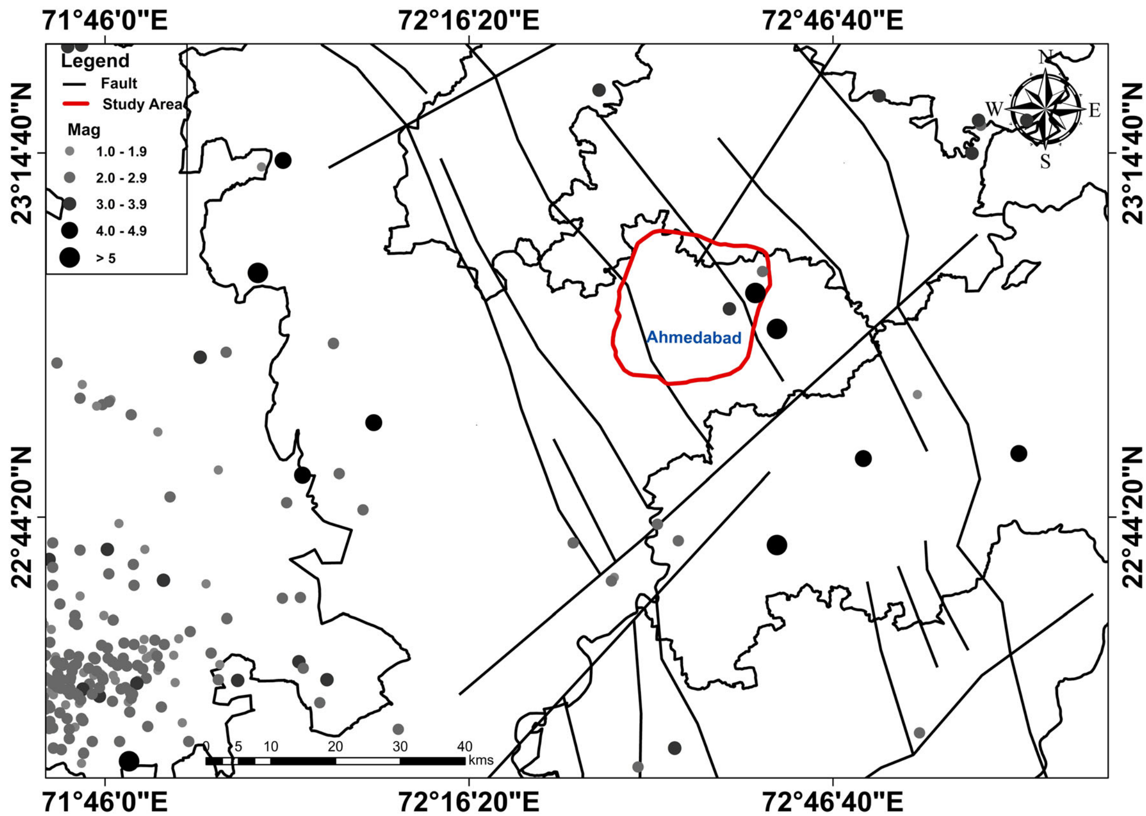

Fig. 2 Epicenters of earthquakes M ≥ 1.5 occurring in the Ahmedabad and surrounding region during the period 1840 to 2016 (mark Ahmedabad in the map)

Many modern seismic codes of the developed countries like America, Europe, and Japan have produced abundant and geophysical data and have incorporated site effects in their codes (IBC 2009; UBC 97 1997; BSSC 2003; EC8 2011). The sites can be classified based on any one of the following three parameters, i.e., undrained shear strength (Su), standard penetration resistance (*N*-value), and shear wave velocity (Vs). The design spectrum determined 30-m average Vs values (Borcherdt 1994), 30-m average standard penetration resistance (N30), and undrained shear strength (Su), are also used for site classification. Both the Uniform Building Code (UBC 1997) and Eurocode 8 (EC8 2011) use V_{S30} to classify the sites, for earthquake engineering design. The Vs can directly be measured from field tests or can be estimated from the existing correlations between *N*-values and Vs (Hansancebi and Ulusay 2007). The V_{S30} estimation is useful for seismic zonation studies (Kockar et al. 2010). The site characterization of the Ahmedabad City is carried out based on average shear wave velocity to 30 m (V_{S30}). The V_{S30} of the study area is estimated from the PS-logging and the MASW surveys and ranges from 163 to 380 m/s. The V_{S30} distribution in Ahmedabad is shown in Fig. 3. According to NEHRP (BSSC 2003), the study area comes under the site class D in which V_{S30} ranges from 180 to 360 m/s (Table 2).

Surface peak ground acceleration

Rout et al. (2019) prepared a probabilistic hazard map of Gujarat region at bedrock level (Vs 760 m/s) using an updates earthquake catalog from 1668 to 2016 by considering seven seismogenic zones in Gujarat based on the tectonic set-up and seismicity, which includes Cambay basin as a separate zone. The seismicity parameters were estimated for each seismogenic zone. The ground motion values were estimated at the B/C boundary (Vs 760 m/s) using the ground motion predication equation (GMPEs). The ground motion prediction equations (GMPE) are important in the seismic hazard analysis of any region. The accuracy of these prediction equations depends upon the data and methodology used to arrive at such relationships. These attenuation equations directly influence the hazard results. Generally, region-specific ground motion equations are preferred for the hazard estimation. For Gujarat region, few attenuation relations are developed using strong motion earthquake data. Mandal (2009) has developed a ground motion attenuation equation for the Kachchh region, Gujarat in terms of peak ground acceleration (PGA) by using aftershock data of 2001 Bhuj earthquake. NDMA (2011) has developed an attenuation equation for all the seven tectonic regions of India with different coefficients, and this equation is valid for site class A (V_{S30} > 1500 m/sec). The Eastern North

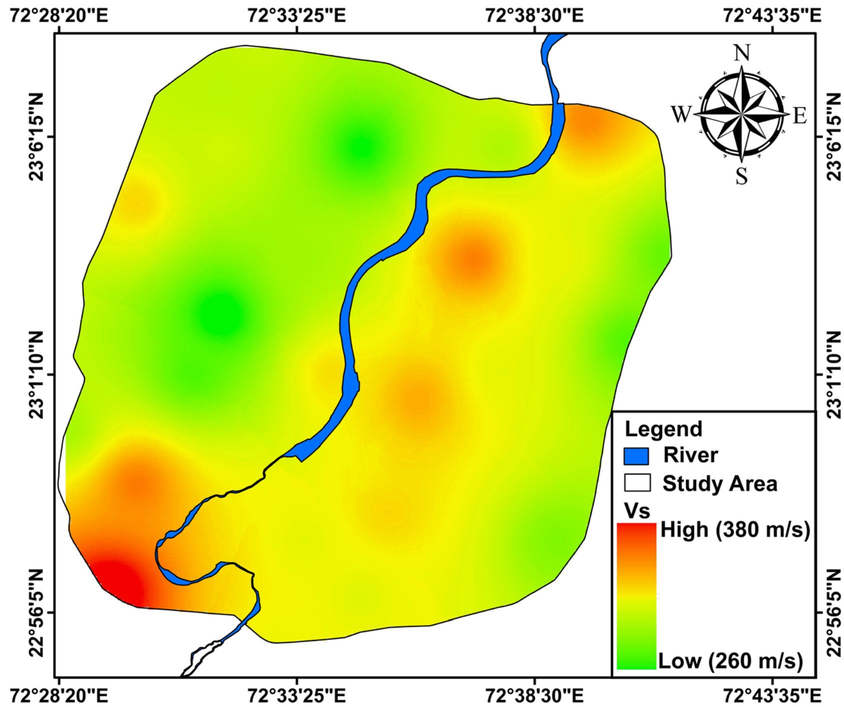

Fig. 3 Distribution of shear-wave velocity to 30 m (VS30) of Ahmedabad City

America (ENA) is considered to be a stable continental region like Gujarat (Talwani 2014). Atkinson and Boore (2006) have developed a new ground motion equation for ENA using a stochastic finite-fault model for hard rock and soil types. The equations are valid for the hard rock site ($V_{S30} \geq 2000$ m/sec) or NEHRP site class A. Rout et al. (2019) has used these GMPEs for PSHA with weightage of 40% to Mandal (2009), 40% to NDMA (2011), and 20% to Atkinson and Boore (2006), and the PGA has been calculated at different return periods.

The ground motions estimated at B/C boundary needs to be brought to surface level by applying amplification factors. The amplification factor for different sites are derived based on empirical relationship proposed by Choi and Stewart (2005) using the average shear wave velocity in the upper 30 m (V_{S30}). By multiplying the amplification factor derived by Choi and Stewart (2005) with the ground motion value at B/C boundary level, the PGA is estimated at the surface level (Fig. 4). It is observed that the amplification is in the range 1.3–1.6 at Ahmedabad. It has been found that the PGA at surface varies between 108 and 144 cm/s^2 for 2% PE in 50 years and between 52 and 65 cm/s^2 for 10% PE in 50 years.

Table 2 NEHRP classification of soils/rocks based on V_{S30}

Soil type	Classification	*N*	Vs (m/s)
Soft clays/sand	E	< 15	< 180
Stiff soil	D	15–50	180–360
Dense soil/soft rock	C	> 50	360–760
Firm to hard rock	B	-	760–1500
Hard rock	A	-	> 1500

Factor of safety against liquefaction

Liquefaction hazard analysis was carried out based on SPT-N value, PGA, plasticity index, density, ground water level (GWL), and fine content (Fioravante et al. 2013; Cavallaro et al. 2018), using methodologies suggested by Seed and Idriss (1971), Youd et al. (2001) and Idriss and Boulanger (2006). The *N* values obtained from the standard penetration test are corrected to obtain the standardized $(N_1)_{60}$ (Robertson and Wride 1997). The measured SPT *N* values were also corrected for an overburden pressure in accordance with the recommendations made by NCEER (1997) and Kayen et al. (1992). The earthquake loading on the soil is expressed by the cyclic stress ratio (CSR). The simplified method suggested by Seed and Idriss (1971) is used to find out the CSR using following equation:

$$\mathrm{CSR} = 0.65\left(\frac{\alpha max}{g}\right)\left(\frac{\sigma_{\mathrm{vo}}}{\sigma_{\mathrm{vo}}}\right)\mathrm{rd} \qquad (1)$$

where 0.65 (α_{max}/g) = 65% of the peak cyclic shear stress; αmax = peak horizontal acceleration at the ground surface generated by the earthquake; *g* = acceleration due to gravity; σ_{vo} = total overburden stress; σ_{vo}' = effective overburden stress; and rd = stress reduction coefficient. The strength of

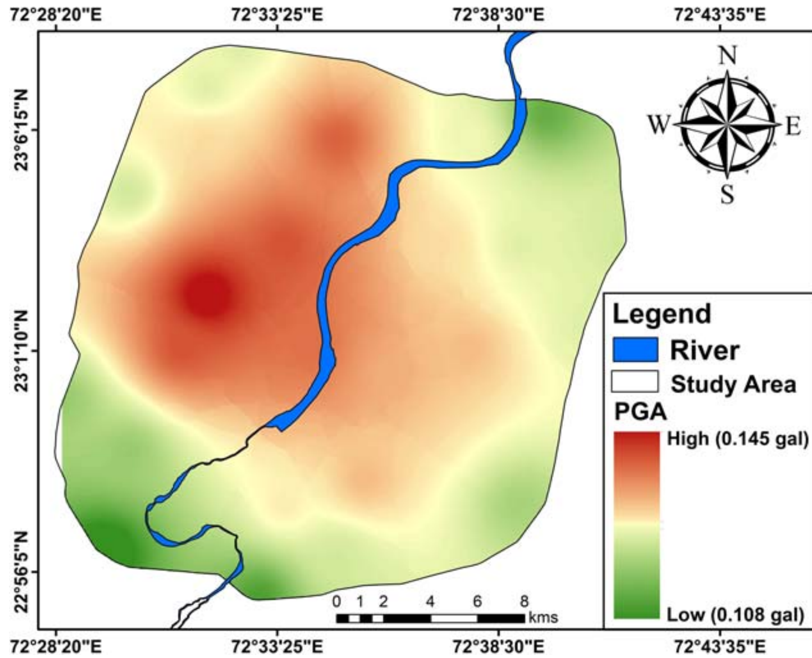

Fig. 4 Distribution of surface peak ground acceleration in Ahmedabad City

the soil (capacity of soil) to resist liquefaction is expressed in terms of cyclic resistance ratio (CRR). The liquefaction resistance of the soil depends on how close the initial state of the soil is to the failure.

$$\mathrm{CRR} = \exp\left[\left(\frac{(N1)60\mathrm{CS}}{14.1}\right) + \left(\frac{N1)60\mathrm{CS}}{126}\right)^2 - \left(\frac{N1)60\mathrm{CS}}{23.6}\right)^3 + \left(\frac{N1)60\mathrm{CS}}{25.4}\right)^4 - 2.8\right] \tag{2}$$

Liquefaction resistance of the soil depends on how close the initial state of soil is to the state corresponding to the failure. The N value $(N1)_{60}$ is further corrected for the fine content, based on the revised boundary curves as derived by Idriss and Boulanger (2006) for cohesion-less soils to get $(N1)_{60\mathrm{CS}}$, i.e., corrected N value for clean sand (Idriss and Boulanger 2006). The factor of safety (FOS) was calculated by the ratio of the CRR and the CSR and categorized as critical, moderate, low, and very low to classify the liquefaction probability within a region.

$$\mathrm{FOS} = \frac{\mathrm{CSR}}{\mathrm{CRR}} \tag{3}$$

In the Fig. 5, it is found that the NW, NE, central, and the southern parts of the city have very low liquefaction potential whereas the eastern, western, and the SW parts show high to moderate liquefaction probability.

Methodology

We tried to prepare an integrated seismic hazard map using various geophysical, geotechnical, and geological attributes following the analytical hierarchy process (AHP). The AHP technique is a multi-criteria method for scientific evaluation of the decision-making process proposed by Saaty (1987) and adopted for seismic hazard analysis. In this process, hierarchical structures are used to enumerate the relative significances of a given set of features on a ratio scale, which is based on the discretion of the researcher (Saaty 1987, 1988, 2003, 2008; Mohanty et al. 2007).

The hazard index is an integrated factor, and it depends on weights and ranks of the seismological and geological attributes. The attribute weights may be assigned based on their contribution to the seismic hazard. The rank can be assigned within an attribute against their values closer to hazards. Usually higher rank is assigned to an attribute, which is considered to play a significant role in deciding the overall seismic hazard of a region.

In this work, four attributes, namely, surface peak ground acceleration (PGA), shear-wave velocity to 30 m (V_{S30}), liquefaction potential, and geology/geomorphology are taken for the preparation of integrated seismic hazard map for Ahmedabad region. Since the region has thick pile of sediments resting over the basement, we assigned highest weight to PGA followed by V_{S30}, liquefaction, and geology/

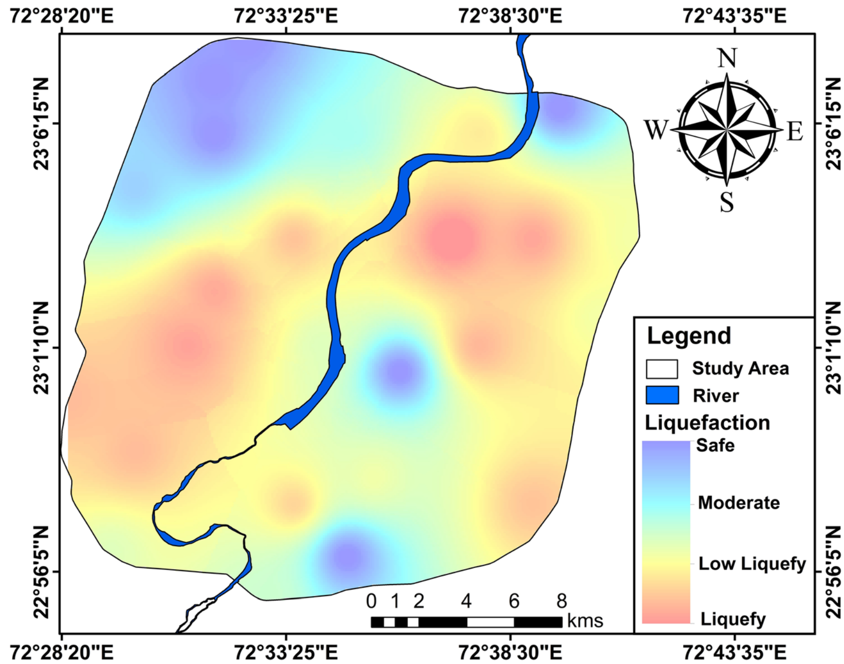

Fig. 5 Distribution of factor of safety against liquefaction in Ahmedabad City

geomorphology (Table 3). The element matrices are prepared on a scale of 1–4. In this matrix, 1 indicates that both elements are equally important. Moreover, 4 implies that one is more important than the other element. Here, if one element is less important than other, it is indicated by the reciprocal, (i.e., 1/4). The pairwise comparison matrix is used to derive the normalized weight of each element. These calculated weights are used in deriving the weighted sums of rating of each area of the polygons of the mapped layers (Ganapathy 2011). The matrix prepared for the comparison is used for obtaining the normalized weights of each element. It is done by averaging the values of each row of the matrix. These weights also add up to 1 and can be used in deriving the weighted sums of rating for each region of polygons of the mapped layers. The different features can also be normalized between 0 and 1 to ensure that no layer can be influenced beyond its determined weight (Nath 2004). The normalization is carried out using the Eq. 4

$$xi = \frac{Rj - R\min}{R\max - R\min} \tag{4}$$

Here, R_j represents row rating; Rmin and Rmax show the minimum and the maximum rating of a particular layer (Nath 2004; Mohanty et al. 2007).

From this AHP, one spreadsheet is designed to calculate the weights of each layer. The pair-wise comparison with multiple criteria can be done. The calculations of the weights are done outside the GIS platform. The matrix is prepared for four attributes (Table 3) depending on their contribution to the hazard assessment. The PGA is assigned the highest weight. A similar type of approach for the seismic microzonation studies was successfully utilized by many researchers (Nath 2004; Mohanty et al. 2007; Ganapathy 2011). The weights for attributes PGA, V_{S30}, liquefaction and geology/geomorphology are 0.4, 0.3, 0.2, and 0.1, respectively. The normalized rank of each thematic layer for integration in GIS platform is shown in Table 4. The integration will lead to an integrated seismic hazard map of the studied region.

Results and discussions

The lithological variations delineated from 23 boreholes suggest that the Ahmedabad City area made up of different layers of gravel, sand, and silty-clay (Dwivedi et al. 2017). The sediment layers encountered in the boreholes have shown distinct variations in their thickness and shapes from location to location. The index properties in the study area show variations in the characteristics of the soil. Irrespective of the location of borehole the top 3 m of the sedimentary sequences comprised of sandy silts to silty sand with clay. The boreholes 1, 2, 4, 6, 7, and 8 have relatively high concentration of finer sediments in the top 6 m, as they are located away from the main Sabarmati river, whereas, boreholes 3, 5, 9, 10, and 11 have higher concentration of sand as they fall near the Sabarmati River (Fig. 6). All the boreholes show presence of sandy sediments between 6 and 18 m, except at boreholes 4 and 6. At depths 18–30 m, all boreholes show silty—clayey sediments except at boreholes 1, 3, 5, and 10, which are located in palaeo-dunes and in the vicinity of Kankaria lake. At depths of 30–48 m, all boreholes show intercalations of silty sand and clay, except at boreholes 7, 8, and 10, which show sandy horizons, since they are located near to the main channel of the Sabarmati River. Similarly at depths 48–70 m, all

Table 3 Assigned weights for Integration in GIS platform

Themes	Surface peak ground acceleration	Shear-wave velocity (V_{S30})	Factor of safety against liquefaction	Geology/ geomorphology	Weightage
Surface peak ground acceleration	1	4/3	4/2	4/1	0.4
Shear-wave velocity (V_{S30})	3/4	1	3/2	3/1	0.3
Factor of safety against liquefaction	2/4	2/3	1	2/1	0.2
Geology/geomorphology	1/4	1/3	1/2	1	0.1

boreholes show dominantly clayey horizons, except at boreholes 6, 7, and 10, which show silty sand horizons. Also, the boreholes 1 and 2 show coarsening of strata at depths of 57–70 m. The bottom-most strata at depths of 70–81 m of all the boreholes show mostly clayey horizons, except at borehole 8, which show the presence of silty sand. The reason of coarsening of horizons at deeper depths is indicative of the change in the hydrodynamic regime of the Sabarmati river. The boreholes closer to the main Sabarmati river show intercalations of sandy to silty-clayey horizons, which could be related to the change in flux of the Sabarmati river in past times owing to change in climatic conditions. On the western side of the river, a paleochannel was found ~ 5.0 km away from present course (Goel 2001).

The water-table is generally deeper in the city except in boreholes 08, 07, and 20, where the water-table is at 3.5 m, 5.2 m, and 6.0 m, respectively. The specific gravity (~ 2.58–2.75) of the samples imply that the soil in the region is clayey and silty sand. The density (~ 1.3–2.15 gm/cc) implies that the soil is loamy. The void ratio found in the region (~ 0.36–0.80) generally support favorable conditions for local shear failure. The plasticity index (~ 5–35) indicates that the soil consist of clay with intermediate plasticity. The estimated values of cohesion (~ 0.1–0.9) and the angle of internal friction (~ 15–35) indicate that the soil has moderate to high shear strength. The areas like Vasna, Paldi, Satellite, Chandola, Isanpur, and Maninagar show very low *N* value of ~ 10–30 at shallow depth, indicating inadequate soil strength. These areas are covered by dunes and sand sheets.

The average shear-wave velocity (V_{S30}) of the top 30 m is an important parameter for site characterization. The site classification scheme defined in NEHRP (1997) and Uniform Building code (UBC) (1997) are based on the V_{S30} values. The north-eastern, central, and south-western parts (Fig. 3) adjacent to the Sabarmati River show high V_{S30} (300–360 m/s) than the western and north-western parts (265–300 m/s). The lowest V_{S30} of about 205 m/s is observed in the western part of the Ahmedabad and the highest (380 m/s) is observed in the south-western part of the city. Over all, V_{S30} of the study area is in the range of 265 to 360 m/s. The western portion may comprise of more recent sediments as compared with eastern section. This region can be classified as D-type soil (stiff soil) according to NEHRP classification. The areas adjacent to the right bank of the Sabarmati river show lower V_{S30} as compared with the left bank shown in Fig. 3. This may be due to the presence number of ponds that were later reclaimed and a paleochannel of Sabarmati river (Fig. 1) that is present ~ 5 km west on the west-central side of the Sabarmati river (Goel 2001). The presence of unconsolidated sediments in top 6 m lowered the V_{S30} values in this region. This region may expect high amplification during large earthquake.

In this study, we have also estimated the level of ground motions expected at different sites using probabilistic

Table 4 Normalized ranking of attributes

Theme	Values	Weightage	Rank	Normalized rank
Surface peak ground acceleration in (g)	0.108–0.119	0.4	3	0
	0.120–0.130		2	0.5
	0.131–0.145		1	1
Shear-wave velocity (V_{S30})	< 180	0.3	1	1.0
	180–360		2	0.5
	> 360		3	0
Factor of safety against liquefaction	1.5–2.5	0.2	1	1
	2.5–4.0		2	0.5
	> 4		3	0
Geology	Bad land	0.1	1	1.0
Geomorphology	Dunes sand		2	0.5
	Fluvial deposit		3	0

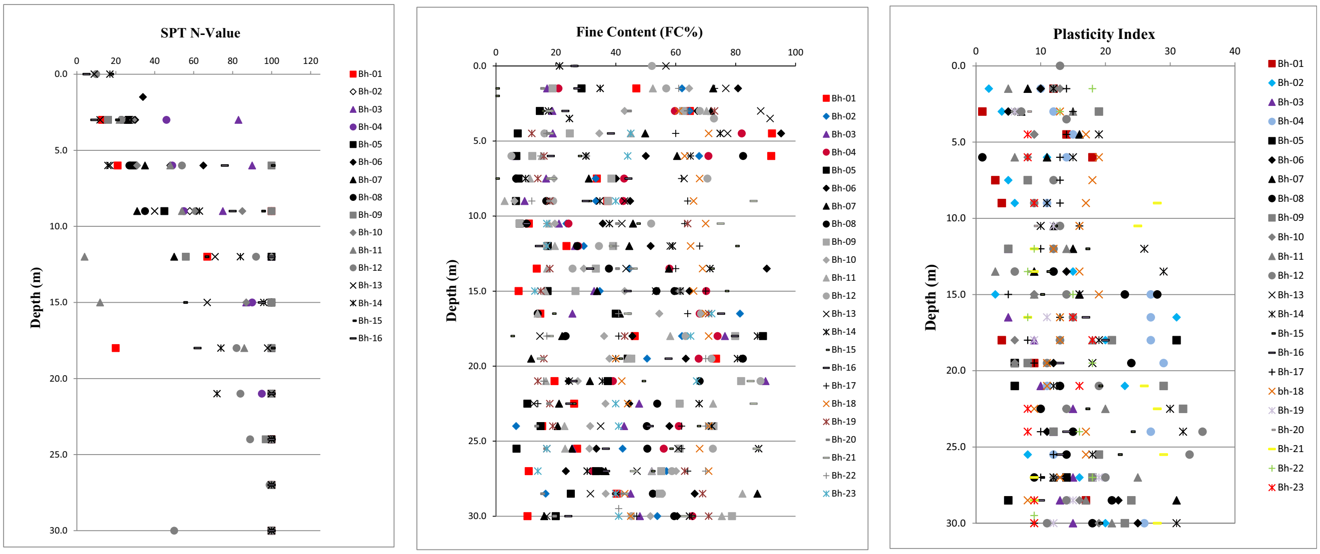

Fig. 6 The variation of index properties of the soil in Ahmedabad region

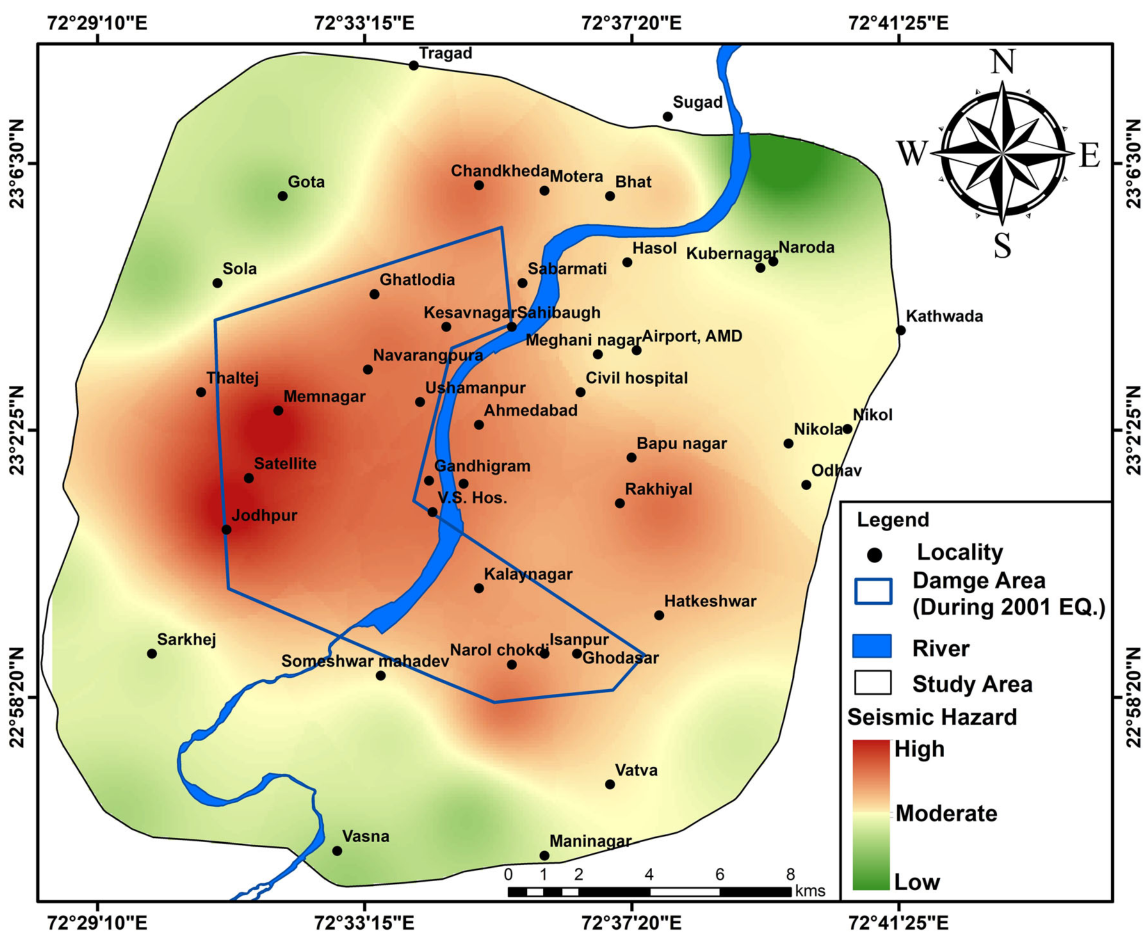

Fig. 7 Seismic microzonation Map of Ahmedabad City

approach. The PGA varies between 0.108 and 0.144 gals for 2% PE in 50 years at surface level. This is equivalent to PGA from a maximum credible earthquake (MCE). It is seen that PGA is maximum on the western side of Ahmedabad City where traces of a paleochannel is found. The high PGA is due to low V_{S30} and high amplification at these sites as local site response is included while estimating PGA at the surface. These PGA values along with index properties of soils determined by geotechnical investigations are helpful in estimating the liquefaction potential at various sites in the city using methodologies suggested by Seed and Idriss (1971), Youd et al. (2001) and Idriss and Boulanger (2006). It was found that southwestern part of the Ahmedabad City where the footprints of a paleochannel are present has high to moderate liquefaction potential.

The final seismic hazard assessment map is prepared by integrating different inputs obtained from geological, geotechnical, and geophysical investigations. For integration, we have considered PGA at surface, V_{S30}, liquefaction potential and geology and geomorphology as attributes with weightages of 0.4, 0.3, 0.2, and 0.1 respectively (Table 3). The normalized ranks are provided to each layer of an attribute based on their values (Table 4). All the thematic layers are integrated on a GIS platform that results in an integrated seismic hazard map of Ahmedabad City. The integration was performed using UNION (SET theory). The entire city is categorized as having low, medium, or high seismic hazard (Fig. 7). The west-central part of Ahmedabad comprising of Satellite, Memnagar, and Jodhpur has highest seismic hazard (Fig. 7). This may be due to the fact the region has low V_{S30}, has high amplification, and has high liquefaction potential. This area has a paleochannel of Sabarmati due to which the unconsolidated sediments are present at the top. The east-central portion comprising of Rakhiyal, Lal Darwaja, and Isanpur has moderate to high hazard. This region has lakes and ponds, most of which are reclaimed in recent years. During 2001 Bhuj earthquake (M_W7.6), though the epicenter was 240 km from Ahmedabad, 130 reinforced concrete buildings were collapsed in Ahmedabad, and 752 people lost their lives (EERI 2002). The damaged area is marked in Fig. 7. The damaged area comprises of west-central and east-central regions of the city. The integrated seismic hazard map prepared by us show moderate to high hazard in those areas where damages were observed in 2001 earthquake. Though local site-effect played a role in damages, poor construction practices is also one of the reason for more damages (Sairam et al. 2018). The eastern most part of the city, comprising of Vastral and Naroda area, comes under the safe category. The soil is stiff in this area as compared to the soils of the western part of the city. In the northern part, the Chandkheda area and its surroundings are also categorized in the safe to moderate category.

Conclusions

In this study, micro-level seismic hazard assessment of Ahmedabad City located in the western Indian state of Gujarat is carried out. The city declared as world heritage city by UNESCO. The city is situated in the middle of the moderately active Cambay rift. The city mushroomed across the banks of Sabarmati river that flows in the middle of the city. The city is located on 300-m thick quaternary sediments. Most part of the city is covered by flood plain of Sabarmati river. A paleochannel of Sabarmati river is also present in the central part of the city. The city is surrounded by east and west marginal faults of Cambay rift besides several transverse faults that crisscrossed the area. Not much seismicity is observed in this part of the rift barring few earthquakes of magnitude between 3.7 and 5.7. The region is vulnerable not only from a local large earthquake but also from a large earthquake in Kachchh region, which witnessed three large earthquakes in the last 200 years, namely 1819 Kachchh (M_W7.8), 1956 Anjar (M_W6.0), and 2001 Bhuj (M_W7.6). Significant damages were observed in Ahmedabad during 1819 and 2001 earthquakes. A total of 23 boreholes were drilled varying in depths from 35 to 80 m spread all over the city. The index properties of the soil samples were determined in the field/lab in addition to SPT-N values for estimating the liquefaction potential. It was found that western and eastern parts of the city have high probability of liquefaction whereas northern and southern parts are safe. Geophysical investigations were also carried out at 65 sites (PS logging at 11 sites and MASW at 54 sites) to constrain the V_{S30} values. It was found that the entire city except a pocket in the southwestern part of the city is classified as D-type soil as per NEHRP. The V_{S30} values vary between 260 and 380 m/s. The V_{S30} values are lower at the sites located on the right bank of Sabarmati river and higher on the left bank. It seems that the presence of a paleochannel of Sabarmati river on the right bank is lowering the V_{S30} values as the region has unconsolidated sediments. The level of ground motions in terms of PGA expected in the region from local and regional earthquakes are also estimated using PSHA methodology for 2% PE in 50 years that corresponds to maximum credible earthquake. The PGA is first determined at engineering bedrock (V_S 760 m/s) and then brought to the surface level using V_{S30} information at each site. Here too, it was observed that areas in and around paleochannel has more PGA as compared with other regions. An integrated hazard map considering the PGA, V_{S30}, liquefaction, and geomorphology as attributes is prepared using AHP on a GIS platform by integrating thematic layers of all attributes. The city area is categorized as low, moderate, and high in terms of seismic hazard. It is observed that the west-central part of Ahmedabad coinciding with areas occupied by paleochannel has the highest hazard whereas northeastern, northwestern, and southern parts have low hazard. We inferred that presence of paleochannels, lakes, rivers, and reclaimed land controls the seismic hazard in a region. The integrated hazard map was compared with damages during 1819 Kachchh (M_W7.8) and 2001 Bhuj (M_W7.6) earthquakes. It was found that major damages reported from these two large earthquakes coincide with high hazard areas, validating the integrated hazard map. The hazard map can be used for the urban planning and infrastructural development.

Acknowledgement The authors are grateful to Dr. M. Ravi Kumar, Director General, Institute of Seismological Research, ISR Gandhinagar, Gujarat, India for his kind support and encouragement for doing this research work. The authors are also grateful chief editor Resat Ulusay and the reviewers for their valuable suggestions, which have improved the manuscript.

Funding information The study was supported by the Ministry of Earth Science under the project MoEs/P.O.(Seismo)/1(41)/2009.

References

Aki K (1988) Local site effect on strong ground motion. Proc Earthq Eng Soil Dyn II, 27-30 June. ASCE, pp 103–155

Atkinson GM, Boore DM (2006) Earthquake ground-motion prediction equation for eastern North America. Bull Seismol Soc Am 96:2181–2205. https://doi.org/10.1785/0120050245

Bard PY, Czitrom C, Durville JL, Godefroy P, Meneroud JP, Mouroux P, Pecker A (1995) "Guidelines for seismic microzonation studies" Published by delegation of 54 major risks of the French ministry of the environment-direction for prevention, pollution and risks, p–50

BIS (2002) IS 1893–2002, Indian standard criteria for earthquake resistant design of structures, part 1 - general provisions and buildings. Bureau of Indian Standards, New Delhi

Borcherdt RD (1994) Estimates of site dependent response spectra for design (methodology and justification). Earthquake Spectra 10:617–653

BSSC (2003) NEHRP recommended provision for seismic regulation for new buildings and other structures (FEMA 450), Part 1: Provisions. Building Safety seismic council for the federal Emergency Management Agency, Washington D. C.

Caruso S, Ferraro A, Grasso S, Massimino MR (2016) Site response analysis in Eastern Sicily based on direct and indirect vs measurements. 1st Imeko Tc-4 International Workshop on Metrology for Geotechnics, Benevento (Italy), pp 115–120

Cavallaro A, Grasso S, Ferraro A (2016) Study on seismic response analysis in "Vincenzo Bellini" garden area by seismic dilatometer Marchetti tests. - Proceedings of the 5th International Conference on Geotechnical and Geophysical Site Characterization, ISC 2016"

Cavallaro A, Capilleri P, Grasso S (2018) Site characterization by in situ and laboratory tests for liquefaction potential evaluation during Emilia Romagna Earthquake; Geosciences, Special Issue: Site-Specific Seismic Hazard Analysis: New Perspectives, Open Issues and Challenges. Geosciences 8(7), 242):1–15

Census of India (2011) Provisional population totals paper 2, Volume 1 of 2011 Rural-Urban Distribution GUJARAT Series-25, http://censusgujarat.gov.in

Choi Y, Stewart JP (2005) Nonlinear site amplification as function of 30m shear wave velocity. Earthquake Spectra 21:1–30. https://doi.org/10.1193/1.1856535

Chopra S, Kumar D, Rastogi BK (2010) Estimation of strong ground motions for 2001 bhuj (mw7.6), India earthquake. Pure Appl Geophys 167:1317–1330. https://doi.org/10.1007/s00024-010-0132-y

Chopra S, Kumar D, Rastogi BK et al (2012) Deterministic seismic scenario for Gujarat region, India. Nat Hazards 60:517–540. https://doi.org/10.1007/s11069-011-0027-y

Chopra S, Kumar D, Rastogi BK et al (2013) Estimation of seismic hazard in Gujarat region, India. Nat Hazards 65:1157–1178. https://doi.org/10.1007/s11069-012-0117-5

Dwivedi VK, Dubey RK, Thockhom S, Pancholi V, Chopra S, Rastogi BK (2017) Assessment of liquefaction potential of soil in Ahmedabad Region, Western India. J Indian Geophys Union 21(2):116–123

Earthquake Engineering Research Institute (EERI) (2002) 2001 Bhuj, India, earthquake reconnaissance report. Earthq Spectra, pp 18–398

Eurocode 8 (2011) Seismic design of buildings worked examples, Workshop "EC 8: Seismic Design of Buildings", Lisbon, Feb. 10-11, 2011, 3-522

Field EH, Jacob KH, Hough SE (1992) Earthquake site response estimation: a weak motion case study. Bull Seismol Soc Am 82:2283–2307

Fioravante V, Giretti D, Abate G, Aversa S, Boldini D, Capilleri PP, Cavallaro A, Chamlagain D, Crespellani T, Dezi F, Facciorusso J, Ghinelli A, Grasso S, Lanzo G, Madiai C, Massimino MR, Maugeri M, Pagliaroli A, Ranieri C, Tropeano G, Santucci De Magistris F, Sica S, Silvestri F, Vannucchi G (2013) Earthquake Geotechnical Engineering Aspects: The 2012 Emilia Romagna Earthquake (Italy); Proceedings of the 7th International Conference on Case Histories in Geotechnical Engineering, Wheeling (Chicago), 29 April - 4 May 2013, paper no. EQ-5 (ISBN:1-887009-17-5)

Ganapathy GP (2011) First level seismic microzonation map of Chennai city - a GIS approach. Nat Hazards Earth Syst Sci 11:549–559. https://doi.org/10.5194/nhess-11-549-2011

Goel RK (2001) Performance of Buildings during January 26, 2001 Bhuj Earthquake. Department of Civil and Environmental Engineering, California Polytechnic State University, San Luis Obispo, California, pp 1–8

Hansancebi N, Ulusay R (2007) Empirical correlation between shear wave velocity and penetration resistance for ground shaking assessment. Bull Eng Geol Environ 66:203–213

IBC (2009), International Building Code, published by International Codes Council.

Idriss IM, Boulanger RW (2006) Semi-Empirical procedures for evaluating liquefaction potential during earthquakes. Soil Dyn Earthq Eng 26(2-4):115–130. https://doi.org/10.1016/j.soildyn.2004.11.023

ISR (2016-17) Institute of Seismological Research Annual report (https://isr.gujarat.gov.in/sites/default/files/annual-report-2016-17.pdf).

Iyengar RN, Raghukanth STG (2004) Attenuation of strong ground motion in peninsular India. Seismol Res Lett 75:530–540

Kaila KL, Tewari HC, Krishna VG, Dixit MM, Sarkar D, Reddy MS (1990) Deep seismic sounding studies in the north Cambay and Sanchor basins, India. Geophys J Int 103:621–637. https://doi.org/10.1111/j.1365-246X.1990.tb05676.x

Kansas Geological Survey (KGS) (2010) Surfseis: seismic processing software, Version 3. KGS, Lawrence, Kansas

Kayen RE, Mitchell JK, Seed RB, Lodge A, Nishio SY, Coutinho R (1992). Evaluation of SPT-, CPT-, and shear wave-based methods for liquefaction potential assessment using Loma Prieta data, in Technical Report US National Center for Earthquake Engineering Research (NCEER), Vol. 1, 177–204 pp.

Kockar MK, Akgun H, Rathje EM (2010) Evaluation of site conditions for Ankara Basin of Turkey based on seismic site characterization of near-surface geologic materials. Soil Dyn Earthquake Eng 30(1):8–20

Mandal P (2009) Ground-motion attenuation relation from strong-motion records of the 2001 Mw 7.7 Bhuj Earthquake Sequence (2001–2006), Gujarat, India. Pure Appl Geophys 166(3):451–469. https://doi.org/10.1007/s00024-009-0444-y

Merh SS (1995) Geology of Gujarat. Geological Society of India, Bangalore

Mohanty WK, Walling MY, Nath SK, Pal I (2007) First order seismic microzonation of Delhi, India using geographic information system (GIS). Nat Hazards 40:245–260. https://doi.org/10.1007/s11069-006-0011-0

Murty CVR, Goel RK, Goyal A, Jain SK, Sinha R, Rai DC, Arlekar JN, Metzger R (2002) Reinforced concrete structures. Earthquake Spectra 18:149–185

Nath SK (2004) Seismic hazard mapping and microzonation in the Sikkim Himalaya through GIS integration site effects and strong ground motion attributes. Nat Hazards 31:319–342

Nath SK, Sengupta P, Sengupta S, Chakrabarti A (2000) Site response estimation using strong motion network: a step towards microzonation of Sikkim Himalayas seismology. Curr Sci 79: 1316–1326

Nath SK, Vyas M, Pal I, Sengupta P (2005) A seismic hazard scenario in the Sikkim Himalaya from seismotectonics, spectral amplification, source parameterization, and spectral attenuation laws using strong motion seismometry. J Geophys Res 110:B01301. https://doi.org/10.1029/2004jb003199

Nath SK, Thingbaijam KKS, Raj A (2008) Earthquake hazard in the Northeast India - a seismic microzonation approach with typical case studies from Sikkim Himalaya and Guwahati city. J Earth Syst Sci 117:809–831

Nath SK, Raj A, Thingbaijam K, Kumar A (2009) Ground motion synthesis and seismic scenario in Guwahati City–a stochastic approach. Seismol Res Lett 80:233–242

National Center for Earthquake Engineering Research (1997) NCEER workshop on evaluation of liquefaction resistance of soils. T. L. Youd and I.M. Idriss eds., Technical Rep. No. NCEER, 97-022

National Disaster Management Authority (2011) Development of probabilistic seismic hazard map of India technical report. National Disaster Management Authority publication 126. National Disaster Management Authority, Government of India.

NEHRP (1997) Recommended seismic provisions: seismic regulations for new buildings and other structures Part- 1, (FEMA 302).

Pal I, Nath SK, Shukla K, Pal DK, Raj A, Thingbaijam KKS, Bansal BK (2008) Earthquake hazard zonation of Sikkim Himalaya using a GIS platform. Nat Hazards 45:333–377

Pande P, Kayal JR (eds) (2003) Kutch (Bhuj) Earthquake 26 January 2001, in Special Publications, no. 76. Geological Survey of India, Kolkata, India 282pp

Park CB, Miller RD, Xia J (1999) Multi-channel analysis of surface waves. Geophysics 64(3):800–808

Robertson PK, Wride CE (1997) Cyclic liquefaction and its evaluation based on the SPT and CPT, NCEER Workshop on evaluation of liquefaction resistance of soils. National Center for Earthquake Engineering Research, Temple Square, Salt Lake City, Utah 31 December

Rout MM, Chopra S, Sairam B (2019) Probabilistic seismic hazard assessment at surface level for Gujarat state, Western India-an active intraplate region. Soil Dyn Earthq Eng (Under review)

Saaty TL (1987) The analytic hierarchy process: what it is and how it is used. Math Model 9:161–176. https://doi.org/10.1016/0270-0255(87)90473-8

Saaty TL (1988) What is the analytic hierarchy process? In: Mitra G, Greenberg HJ, Lootsma FA, Rijkaert MJ, Zimmermann HJ (eds) Mathematical models for decision support. NATO ASI series (Series F: computer and systems sciences), vol 48. Springer, Berlin

Saaty TL (2003) Time dependent decision-making; dynamic priorities in the AHP/ANP; generalizing from points to functions and from real to complex variables. In: Proceedings of the ISAHP 2003, Bali, Indonesia, August 7–9

Saaty TL (2008) Decision making with the analytic hierarchy process. Int J Serv Sci 1:83. https://doi.org/10.1504/IJSSCI.2008.017590

Sairam B, Singh AP, Patel V, Pancholi V, Chopra S, Dwivedi VK, Ravi KM (2018) Influence of local site effects in the Ahmedabad Mega City on the damage due to past earthquakes in Northwestern India. Bull Seismol Soc Am 108(4):2170–2182. https://doi.org/10.1785/0120170266

Sareen BK, Tandon SK, Bhola AM (1993) Slope deviatory alignment, stream network and lineament orientation of the Sabarmati river system: neotectonic activity in the mid-Late Quaternary. Curr Sci 64:827–836

Seed HB, Idriss IM (1971) Simplified procedure for evaluation of soil liquefaction potential. J Soil Mech Found Div 97(9):1249–1273

Singh SK, Bansal BK, Bhattacharya SN et al (2003) Estimation of ground motion for Bhuj 26 January 2001; Mw7.6 and for future earthquakes in India. Bull Seismol Soc Am 93:353–370. https://doi.org/10.1785/0120020102

Sitharam TG, Anbazhagan P (2008) Seismic microzonation: principles, practices and experiments. EJGE special volume bouquet 08. p. 61. Online: /http://www.ejge.com/Bouquet08/Preface.htm>

Talwani P (2014) Intraplate earthquakes. Cambridge University press, Cambridge, United Kingdom

Tandon SK, Sareen BK, Someshwararao M, Singhvi AK (1997) Aggradation history and luminescence chronology of late quaternary semi-arid sequences of the Sabarmati basin, Gujarat, western India. Palaeogeogr Palaeoclimatol Palaeoecol 128:339–357

UBC-1997 (1997) Uniform Building Code. International Conference of Building Officials, Whittier, California, U.S.A. (Latest Edition: International Building Code-IBC-2000)

Wani MR, Kundu J (1995) Tectonostratigraphic analysisin Cambay basin India: leads for future exploration, Proc. Petrotech Conf. Technology Trends in Petroleum Industry, New Delhi 147-164 pp

Xia J, Miller RD, Park CB (1999) Estimation of near surface shear-wave velocity by inversion of Rayleigh wave. Geophysics 64(3):691–700

Yadav RBS, Tripathi JN, Rastogi BK, Chopra S (2008) Probabilistic assessment of earthquake hazard in gujarat and adjoining region of India. Pure Appl Geophys 165:1813–1833. https://doi.org/10.1007/s00024-008-0397-6

Youd T, Idriss I, Andrus R, Arango I, Castro G, Christian J, Dobry R, Finn W, Harder L, Hynes M (2001) Liquefaction resistance of soils: summary report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils. J Geotech Geoenviron Eng 127:817–833