Ground Response Study for Low Seismic Areas in Central Gujarat Region

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Abstract. Past destructive earthquakes have provided the evidences of influence of local site condition on ground motions. The amplification of ground motion on the surface is strongly affected by the geotechnical characteristics of the region through which the seismic waves travelled. The present study is an attempt to assess the local soil effects in modifying the earthquake ground motion using one dimensional ground response analysis for the central Gujarat region. The input parameters namely shear wave velocity profile, dynamic soil characteristics and ground motions are required to analyze the ground response at 66 locations of the study region. The results have been presented in terms of various maps i.e., peak ground acceleration, predominant frequency, spectral acceleration. Based on the site characterization response spectra have been developed for the central Gujarat region. The results are also compared with the Indian Standard code. Site response study shows that the large amplification are observed in the ground motion at surface level as compare to rock level acceleration.

Keywords: Ground Response Analysis, Seismic Waves, Local Site Conditions, Peak Ground Acceleration

1 Introduction

Local site conditions play major role in performance of building during any earthquake event. Many past earthquakes have provided evidences of local site effects during occurrence of seismic events; i.e., 1985 Mexico City, 1989 Loma Prieta, 1994 Northridge, 1995 Kobe, 1999 Colombia, 2001 Bhuj etc. Gujarat is situated in peninsular India with varying zone factors III to IV (IS:1893-2016). Kutch region is having the highest seismicity with zone factor V and central Gujarat is having moderate seismicity with zone factor III. Though Central Gujarat is lying in moderate seismicity zone, it is vulnerable to earthquake hazards due to both near field and far field seismic sources. During 2001 Bhuj earthquake, many multi-storeyed buildings were damaged in Ahmedabad. Though Ahmedabad is located 238 km away from the epicentre of Bhuj earthquake, major hazards were occurred to the structures in Ahmedabad due to local site effects. Hence, effect of local site conditions is an essential tool which needs to consider in estimating surface ground motion for the development of design spectra, spectral acceleration at various time periods, amplification factor and predominant frequency. These outputs have gained critical importance in hazard mitigation, city planning, rehabilitation of the existing structures and disaster preparedness.

Study has been carried out to estimate site response for many cities in India. Rao and Ramana (2009) have used near field and far field simulated ground motion to carry ground response for Delhi region. Synthetic time history considering point source approximation has been generated to carry site response analysis for Bangalore city (Anbazhagan and Sitharam 2008). Bhuj (2001) earthquake was considered as an input to estimate ground motion parameters in Ahmedabad city (Govindraju et al. 2004, Trivedi et al. 2007). Phanikanth et al. 2011 have estimated ground response considering four ground motions (2001 Bhuj, 1989 Loma Prieta, 1989 Loma Gilory, 1995 Kobe) for Mumbai city. Site response analyses of 38 sites in Chennai city have been investigated considering synthetic ground motion parameters (Boominathan et al. 2008). Local site effects have been estimated for Guwahati city considering an earthquake of Mw 8.1 in Shillong plateau (Raghukanth et al. 2008). Site response studies have been carried out in Naliya, Kutch region considering 2001 Bhuj event and 2002 February after shock event of Bhuj earthquake recorded at Bhuj (Thaker et al. 2009). Ground response analysis has been carried out in Surat city considering 10 simulated time histories for near field sources and 2001 Bhuj earthquake ground motion data for far field sources (Thaker 2012).

In present paper, Vadodara city is considered as a study region to carry out one dimensional ground response analysis considering 2001 Bhuj ground motion recorded at basement of passport office in Ahmedabad. Shear wave velocity was estimated at 64 locations in and around Vadodara city through Multi-channel Analysis of Surface Waves (MASW) technique. Around 430 borelog data were collected from various private and public agencies to prepare the soil profile of the study region. Shear wave velocity, soil profile and ground motion of Bhuj earthquake were considered as an input in DEEPSOIL software to carry site response analysis of Vadodara region. The results have been obtained and mapped in terms of Peak ground acceleration (PGA) at surface, spectral acceleration (SA), predominant frequency (PF) for the study region.

2 Study Region

Vadodara is located in central Gujarat region at 22.30°N 73.19°E with zone factor III – 0.16 g (IS:1893-2016). Many historical monuments from the time of Maharaja Sayajirav Gayakwad have established the city as a cultural capital of Gujarat. Vadodara city is the hub of many educational institutes, industries, chemical and petroleum refineries and various large scale enterprises. Many infrastructures are going to construct under the ‘Smart City’ project of Government of India. Vishwamitri River is passing through the entire city spreads loose sediments at the bank of river. Mahi and Dhadar rivers are also flowing through the Vadodara district, which contain alluvial type of soil. In general, varying type of soil layers like silty sand, silty clay, silt of low to high plasticity, clay of low to medium plasticity at different depths have been observed in entire city. As discussed earlier, the local soil stratum plays a crucial role in amplification of ground motions during the earthquake. However, Vadodara is also bounded with Cambay faults, Son Narmada fault and Tapti fault which are having moderate seismicity with moment magnitude of 6.5. Far field tectonic features like Kutch mainland fault, Island belt fault and Allah bund fault are vulnerable seismic sources of the study region which are having the seismicity of moment magnitude more than 7.5. Hence, it is essential to carry seismic hazard study of Vadodara region considering all vulnerable parameters like tectonic sources, seismicity of the region and geotechnical characteristics of local soil. Fig. 1 shows the seismotectonic model of the study region, which depicts seismic sources with past earthquake events of moment magnitude more than 1.5.

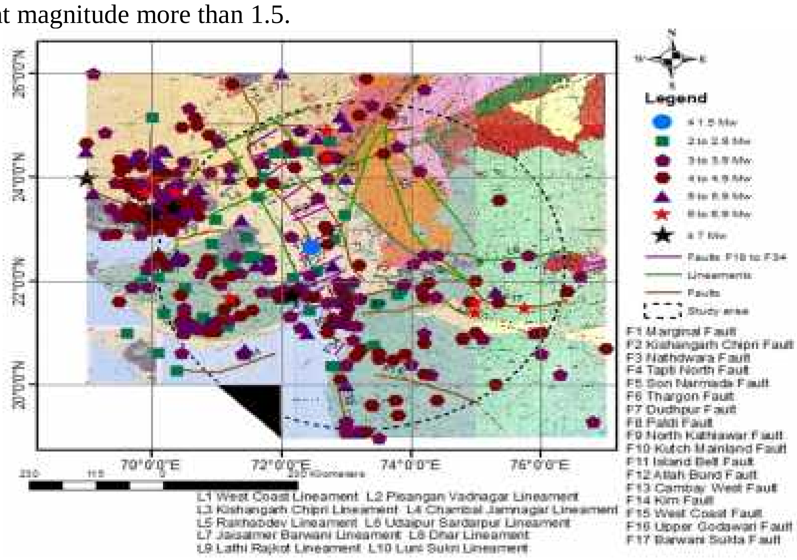

Fig. 1. Seismotectonic Model of Central Gujarat Region (after Mehta et al. 2018)

3 Ground Response Analysis

Site specific ground response analysis is an integral part of seismic hazard study. An attempt has been made to conduct equivalent linear ground response analysis for Vadodara region using DEEPSOIL code (Hashash et al. 2008). The basic input parameters for this code are (a) shear wave velocity profile (b) dynamic characteristics of soil profile like damping curves and strain dependent modulus reduction for each layer of soil (c) ground motions. In equivalent linear approach, ground motion time history is applied at base layer and then transfer functions are determined for different layers of soil considering the dynamic properties of those soil layers. Amplification factors are determined in terms of frequency from the transfer functions for a given soil profile. In next step, each term in the Fourier series of the base motion is then multiplied by transfer function to generate amplified Fourier Spectrum for each layer. The acceleration time history is determined for that layer by the inverse Fourier Transformation. The shear stress and strain time histories are obtained considering the peak acceleration from the input ground motion. Then new values of soil damping and shear modulus are obtained from the damping ratio and shear modulus curves. At last, new transfer functions are obtained and the same process is repeated till the difference between the old and new properties fit in a range of 5% damping.

3.1 Shear wave velocity profile

Shear wave velocity of local soil plays a significant role in amplification of the ground motion. Shear wave velocities were determined at 64 locations of Vadodara city using Multi-channel Analysis of Surface Wave (MASW) technique. Geotechnical details like SPT-N value, type of soil, density, grain size, plasticity index, water table have been extracted from around 430 boreholes which are collected from various agencies. Soil profiles have been generated at 64 locations considering all geotechnical and geophysical attributes. It is observed from shear wave velocity profiles that no variation in shear wave velocity is found after 20 m depth as the soil layer is medium to very stiff after 20 m depth. Hence, in the present paper upper 20 m soil profile has been considered in the analyses.

3.2 Shear Modulus Reduction and Damping Curves

The variation in nonlinear soil properties like shear modulus and damping ratio is quantified from shear modulus reduction versus shear strain and damping ratio versus shear strain curves. Soil type, void ratio, initial stress of effective stresses, plasticity index, over consolidation ratio are some of influential parameters in variation of cyclic stress-strain characteristics of soil. In the present study, generalized curves based on plasticity index presented by Vucetic and Dobry (1991) have been adopted for clayey-silty soils (ML-MI-MH-SC-CL-CI-CH). For sandy-silty soils (SM-SW-SP), shear modulus and damping curves proposed by Seed and Idriss (1970) have been considered.

3.3 Ground Motion

Input of the ground motion is also an important parameter for ground response analysis of the region. Due to unavailability of strong ground motions in Gujarat state, recorded strong ground motion of 2001 Bhuj earthquake has been considered in the present study. 2001 Bhuj ground motion has been recorded at the basement of passport office of Ahmedabad (NEHRP site D). The time history of Bhuj earthquake has been estimated at top of rock by deconvolution process in DEEPSOIL software. The detailed soil profile in terms of shear wave velocity, type of soil and thickness of layer of the recording site has been taken from the literature (Trivedi et al. 2006). Fig. 2 depicts the input ground motion of 2001 Bhuj earthquake at Ahmedabad in the analysis.

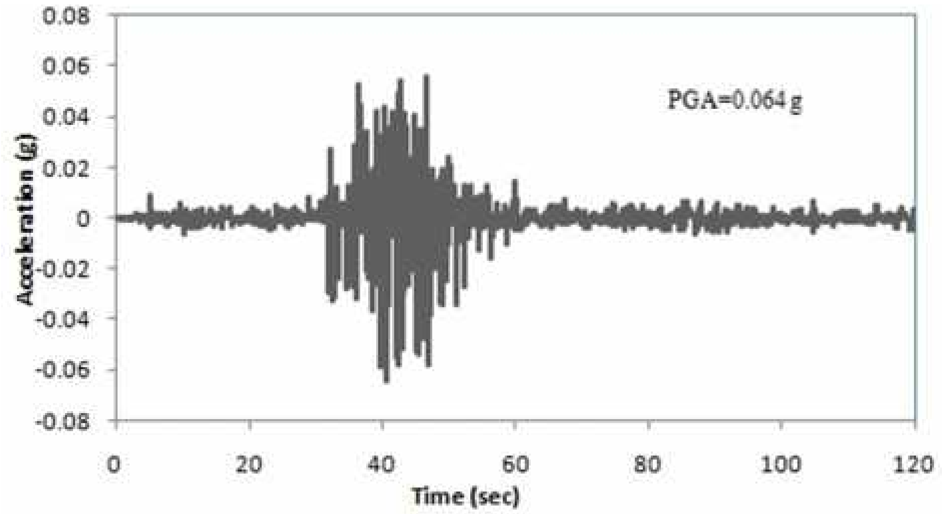

Fig. 2. Input Ground Motion of 2001 Bhuj Earthquake in Ground Response Analysis

4 Predominant Frequency

The predominant frequency (f_p) is defined as the frequency of vibration corresponding to the maximum value of the Fourier amplitude spectrum (Kramer, 1996). The fundamental frequency corresponds to the first mode of vibration of the soil deposit. The largest amplification of soil will occur at the lowest natural frequency. The predominant frequencies of all the locations in the study region have been determined from the average Fourier spectra of the surface ground motions estimated from ground response analysis. The Fourier amplitude spectra with its predominant frequency for some typical sites are presented in Fig. 3.

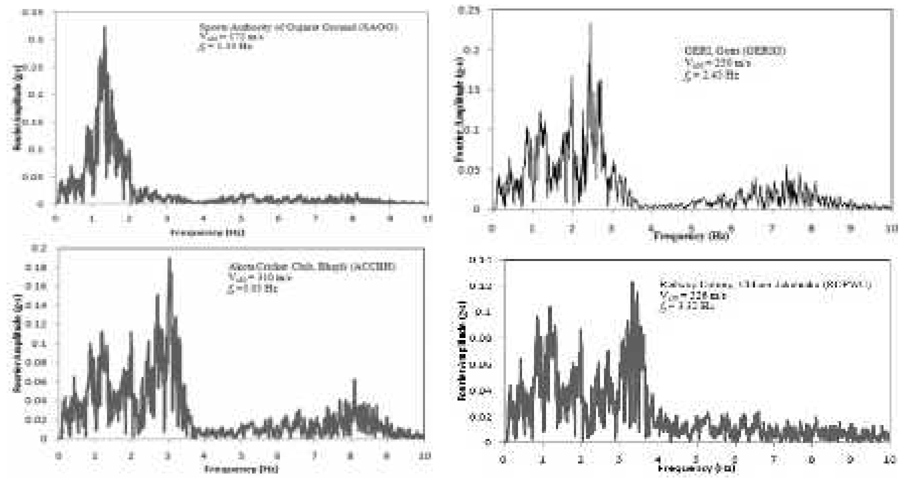

Fig. 3. Fourier Amplitude Spectra at Ground Surface for Typical Sites

Spatial distribution of predominant frequency is presented in Fig. 4 for Vadodara region. The developed map depicts that some areas in east like Bapod, Pariwar Chowkadi, locations in south like Makarpura, Maneja and some locations in north-west like Karodiya, Harinagar are characterized with low frequencies ranging from 1.0 – 2.0 Hz due to loose deposits and low shear wave velocity (V_{s30}). In locations like Sayajipura, Waghodia, Sama, Shaishav School Gotri are associated with moderate frequency of 2.5 Hz. The remaining regions in north, west and central locations and are having highest predominant frequencies ranging from 3.0 – 3.5 Hz because of higher SPT-N value and V_{s30}.

The frequency of an earthquake ground motion influences the behaviour of a structure during seismic event. Natural frequency of any building can be approximately estimated using formula 10/N, where N is the number of stories. Resonance is the phenomena when natural frequency of the building coincides with the predominant frequency of ground motion. The building can be resulted into damage or destruction when resonance occurs. Table 1 depicts the natural frequency of buildings with different stories. Hence it is concluded from Fig. 4 that the structures having more than 5 stories are more vulnerable in north-west locations like Karodiya, Harinagar are having predominant frequencies lowest i.e. 1.0-2.0 Hz in these locations. The structures having 3 to 4 stories are more vulnerable in locations Sayajipura, Waghodia, Sama, Shaishav School Gotri and also some areas in north, west and central part, as these locations are associated with predominant frequency ranging from 2.5 to 3.0 Hz.

Table 1. Natural Frequencies Depending on Type of Buildings

Type of Buildings	Natural Frequency (Hz)
1 storey building	10.0
2 storey building	5.0
3 – 4 storey building	3.33-2.50
5 storey building	2.0
10 storey building	≤ 1.0

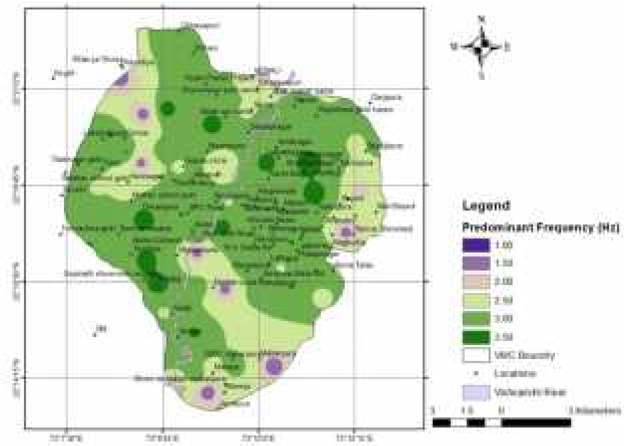

Fig. 4. Spatial Distribution of Predominant Frequencies in Vadodara Region

5 Peak Ground Acceleration at Surface

Seismic response of the subsurface soils can be evaluated through peak ground acceleration. Amplification of the ground motion at surface has been estimated considering local soil characteristics of the region. In the present study, peak acceleration at ground surface has been evaluated at 64 locations in the study region for 2001 Bhuj earthquake strong motion data. The variation of peak ground acceleration with depth at typical locations is depicted in Fig. 5.

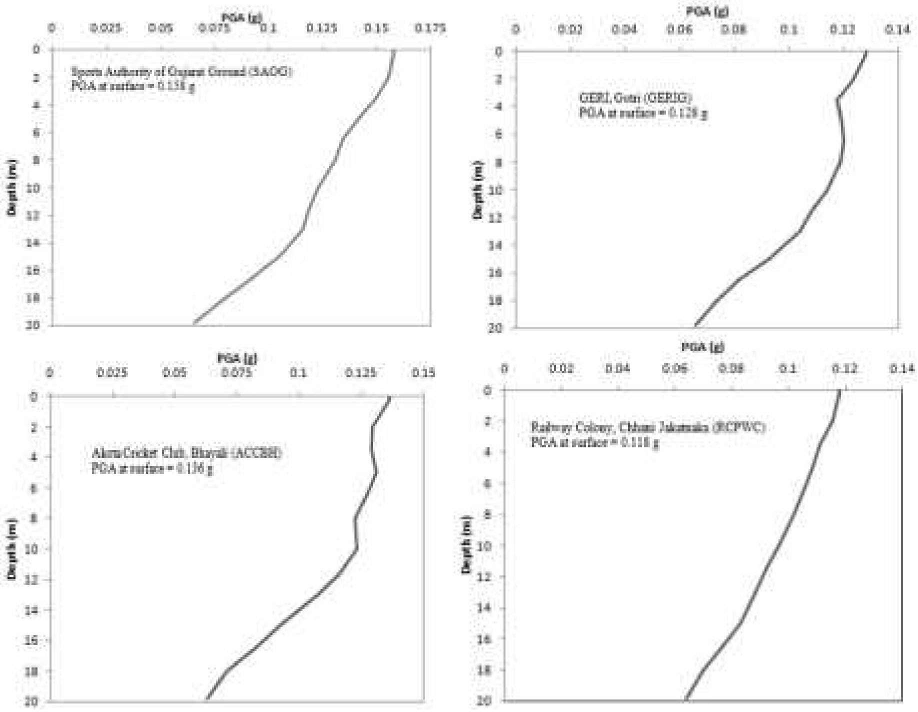

Fig. 5. PGA Variation with Depth for Typical Locations

The spatial distribution of peak acceleration at ground level estimated using Bhuj (2001) earthquake motion has been depicted in Fig. 6. It is observed from Fig. 6 that PGA value at surface ranging from 0.10 g to 0.20 g. The locations like Karodiya, Eklavya Gorwa in north-west, Makarpura, Jambuva in south, Warasiya, Khodiyarnagar, Bapunagar in east have observed lowest PGA value of 0.10-0.12 g. The locations like Mandvi, Dandiya Bazar, Manjalpur, Sama, Gotri, Diwanpura, Tandalja, Atladra, Kalali are associated with 0.13-0.14 g PGA values. The locations like Chhani, Chhayapuri, Hydro Power Project in north; Sayajipura, Moti Bapod, Pariwar Chokdi, Waghodia in east; Nizampura, Sardarbaug, Sayjigung, BPC Road, Alkapuri in centre; Amitnagar, Harni in north-east and Vadsar in south are having highest PGA values ranging from 0.15-0.20 g.

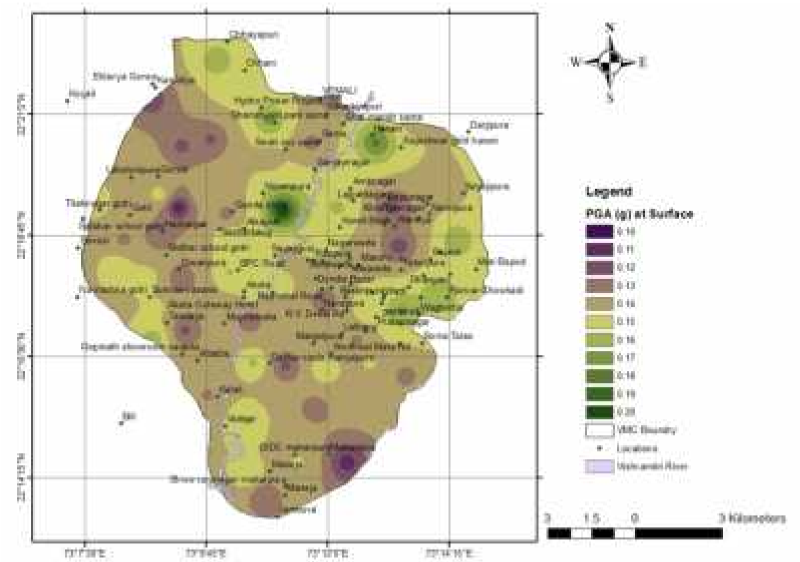

Fig. 6. Spatial Distribution of PGA (g) of Bhuj (2001) Earthquake for Vadodara Region

5.1 Spectral Acceleration

Spectral acceleration values for 0.1, 0.2, 0.3 and 1.0s periods have been computed and mapped in Fig. 7-10. Fig. 7 reveals that locations like Chhayapuri, Chhani, Hydro Power Plant in north; Nizampura, Genda Circle, Alkapuri, BPC Road, Akota in central part of city; Vadsar in south and Amitnagar, Khodiyarnagar, Karelibaug in north-east are having highest spectral acceleration ranging from 0.23-0.25 g at 0.1s. The locations like Bapod, Harni, Mandvi, Dandia Bazar, Manjalpur, Gorwa, Gotri are associated with 0.19 g spectral acceleration value at 0.1s. It is observed from Fig. 8 that areas located in north-east, north-west and central north-east are associated with spectral acceleration values ranging from 0.26-0.28 g at 0.2s. Other locations located in west, south and east part are having moderate value of 0.22 g spectral acceleration at 0.2s. Spectral acceleration values range from 0.2 to 0.8 g at 0.3s period as presented in Fig. 9. Most of the locations in city have observed spectral acceleration of 0.5 g except some locations in east and south at 0.3s. As depicted in Fig. 10, the locations on west side of Vishwamitri River have registered lower spectral acceleration value of 0.18-0.21 g at 1.0s except Gotri, Harinagar, Nizampura Genda Circle, Alkapuri and Sayajigaung. The locations on east side of river are observed spectral acceleration value of 0.24 g at 1.0s. The highest spectral acceleration values ranging from 0.27-0.39 g at 1.0s have been observed in eastern most locations like Bapod, Pariwar Chowkadi and Waghodia.

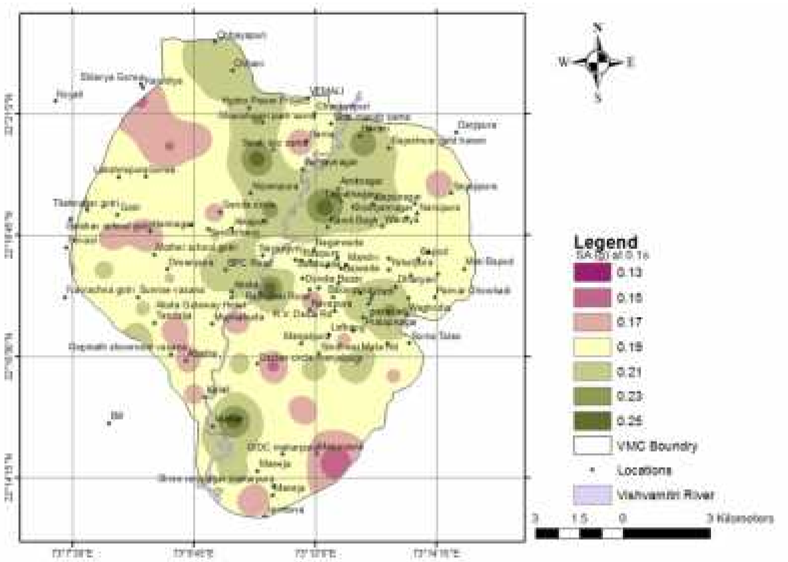

Fig. 7. Spectral Acceleration at 5% Damping at 0.1s Period for Vadodara Region

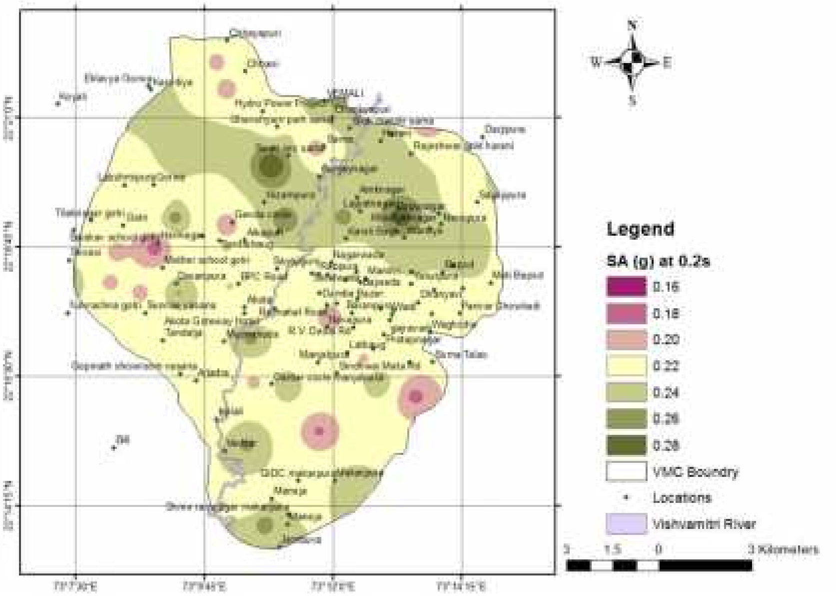

Fig. 8. Spectral Acceleration at 5% Damping at 0.2s Period for Vadodara Region

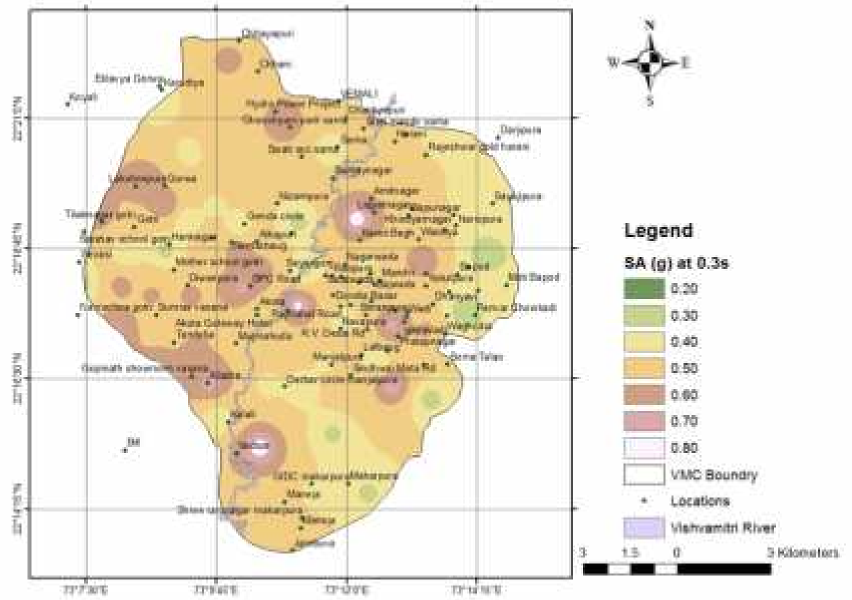

Fig. 9. Spectral Acceleration at 5% Damping at 0.3 s Period for Vadodara Region

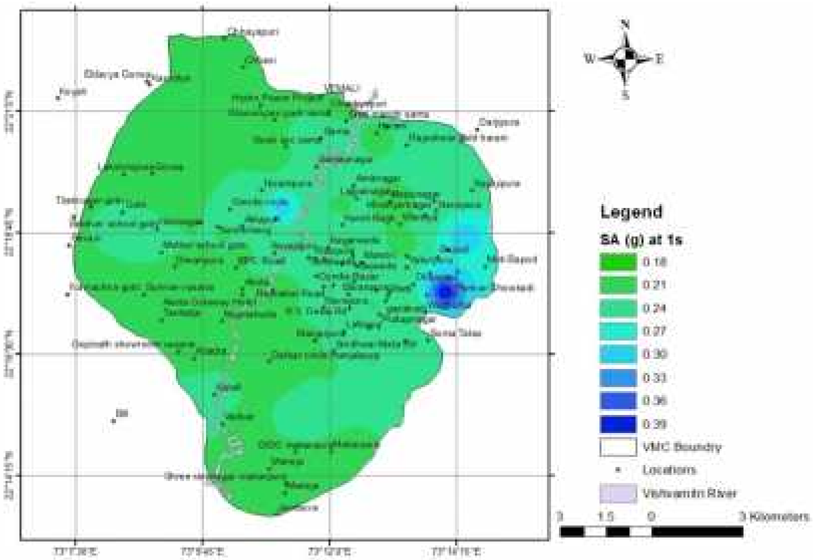

Fig. 10. Spectral Acceleration at 5% Damping at 1.0s Period for Vadodara Region

6 Conclusion

One dimensional equivalent linear ground response analysis has been carried out at 64 locations using DEEPSOIL code for Vadodara region. Gujarat state is not having sufficient recorded ground motion data. Only one strong ground motion data of 2001 Bhuj earthquake has been recorded at basement of Ahmedabad passport office. Hence the actual data of Bhuj (2001) earthquake strong motion have been considered as an input of ground motion in the codes. Shear wave velocity profiles have been computed by performing MASW tests at 64 locations. Soil profiles have been generated from around 430 borelog data collected for Vadodara city. The results are obtained in terms of peak ground acceleration at surface, predominant frequency and spectral acceleration at 0.1, 0.2, 0.3 and 1.0s periods. The PGA values are ranging from 0.10 to 0.20 g at surface for study region. As per IS:1893-2016, Vadodara falls under zone III with zone factor of 0.16 g. Hence, IS code under-estimates PGA value at some locations in east and central part of the study region. Further, PGA value at rock level was evaluated in range of 0.054-0.071 g for 10% probability for 50 years for Vadodara region, which is not the scope of present paper. Hence, large amplification in ground motion has been observed at surface level as compare to rock level acceleration, which shows that local soil plays significant role during an earthquake event. Predominant frequency ranges from 1.0-3.5 Hz in Vadodara city. In north-western part and southern of the city, the predominant frequency lies in the range of 1-2 Hz. In these locations, high rise buildings are more vulnerable to earthquake hazard, as there are chances of occurrence of resonance phenomena. In north, west and central part of the city, predominant frequency ranges from 3.0-3.5 Hz, which reveals that medium rise buildings are more vulnerable in these locations. The results are very much useful in city planning, generating hazard and risk model of the city and micorzonation study of the study region. Further, the results will be used in liquefaction hazard assessment of the Vadodara region.

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