# Identification of Ground Response Parameters of Itanagar City, Arunachal Pradesh, India, Using Varying Seismic Intensities and Equivalent Linear Analysis Approach

**Aditya Kumar Anshu[1], Jumrik Taipodia[2], Shiv Shankar Kumar [3] and Arindam Dey[4*]**

**Aditya Kumar Anshu**
Research Scholar, Department of Civil Engineering, National Institute of Technology, Arunachal Pradesh 791113, India. ORCID No.: 0000-0002-9493-0166
Email: adityaanshu12345@gmail.com

**Jumrik Taipodia**
Assistant Professor, Department of Civil Engineering, National Institute of Technology, Arunachal Pradesh 791113, India. ORCID No.:0000-0001-8943-8014
Email: jtaipodia@gmail.com

**Shiv Shankar Kumar**
Assistant Professor, Department of Civil Engineering, National Institute of Technology Patna, Patna 800005, India. ORCID No.: 0000-0002-1751-8020
Email: k.shiv.ce@nitp.ac.in

**Arindam Dey***
Associate Professor, Department of Civil Engineering, Indian Institute of Technology Guwahati, Assam, India. ORCID No.:0000-0001-7007-2729
Contact No.: +918011002709
Email: arindam.dey@iitg.ac.in

* Corresponding author

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# Identification of Ground Response Parameters of Itanagar City, Arunachal Pradesh, India, Using Varying Seismic Intensities and Equivalent Linear Analysis Approach

**Abstract:** This study assesses the ground response for several typical sites in the Itanagar Region of Arunachal Pradesh, India. The sites were chosen based on their geological characteristics and the seismic history of the region. The region is seismically active and that strong ground motions can be expected in the event of a larger earthquake. In absence of any previous report, the conduct of ground response analysis (GRA) is imperative for this region. This paper reports the GRA of Itanagar region being conducted for the first time in this area. For the exercise, seven borehole locations of the region were selected. Due to the significant effect of strong ground motions on ground response, five different recorded ground motions with peak bedrock acceleration (PBRA) of 0.12g, 0.22g, 0.36, 0.43g and 0.82g are used. In terms of surface acceleration histories, amplification, shear strain and shear stress ratio variations as well as the response spectrum, it is observed that seismic GRA of Itanagar region is significantly affected by the input motion characteristics and soil variability. Given the subsurface characteristics in the area, the significant surface accelerations with high amplifications are noted. Based on the equivalent linear analysis, peak ground acceleration (PGA) in the range of 0.218 g to 1.853 g are observed based on the various input motions, which corresponded to the amplification factors (i.e., ratio of peak ground acceleration to peak bedrock acceleration) in the range of 1.051 to 4.356. Depending upon the soil material present at depths below the ground surface, the GRA results also revealed the deamplification of the propagating seismic waves at certain locations. For all five input motions, the maximum spectral acceleration ranges from 0.725g to 9.153g in the seven locations. The responses from the ground response analysis conducted for the first time in Itanagar region successfully portrays the distribution of PGA, amplification factor and spectral acceleration in the region that would massively help in informed design of structures with the inclusion of these a-priori information.

**Keywords:** Equivalent linear method (EQL); Ground response analysis (GRA); DEEPSOIL; Peak Ground Acceleration (PGA); Amplification factor; Spectral acceleration (SA); Contour maps.

## 1. Introduction

It is well understood that the damaging effects from a seismicity are primarily governed by the geology and soil composition of a particular area [1]. The seismic waves generated during an earthquake propagate through different layers of soil, and their interaction with these layers significantly affects the ground motion characteristics [2]. It is important to consider the location-specific response of underlying soil layers to seismic motions, also referred as site response analysis, in assessing the potential seismic hazards and evaluating the behaviour of structures during earthquakes, which crucially aids in informed seismic design and effective risk mitigation strategiesIn this regard, various purposes can be achieved, such as predicting ground surface motions to establish design response spectra, determining liquefaction hazards based on evolving dynamic stresses and strains, as well as determining earthquake-induced forces leading to possible instability of while evaluating the stability of any geotechnical structures as well as building superstructures. In geotechnical engineering, based on ground response analysis (GRA), it is possible for engineers to tailor their designs to specific site conditions by studying the ground response to various dynamic loads. In relation to GRA studies, apart from the crude linear analyses method, the other competent approaches include frequency-domain based Equivalent linear (EQL) approach for preliminary analyses and the time-domain based nonlinear (NL) time-history approach to capture complex soil behavior. Each of the methods possesses a unique perspective towards the prediction of ground response against seismic challenges. The EQL Method is a valuable tool for GRA as it aids in assessing the soil deformation and ground motion amplification with a relatively lesser computational expense, thereby particularly useful for initial assessments and in case of scenarios with limited data. Several researchers have made successful use of this method for assessing the GRA of different regions around India. It is noteworthy to mention that a non-linear GRA provide more in-depth and realistic results as compared to the same obtained from an EQL GRA. In the equivalent linear analysis, the soil is approximated to behave as a linear elastic material with constant, but iteratively adjusted, shear modulus and damping ratio based on the strain level induced by the input motion. Hence, this method provides conservative results (for e.g., higher peak ground acceleration and amplification factors) [3]. In comparison, nonlinear GRA operates on the realistic stress-strain relationship of soil under cyclic loading, and hence is superlative in capturing the nonlinear behavior of soils under high strain conditions. However, as nonlinear GRA is mostly solved by time-integration method, it is more intricate and time-consuming as compared to the simplicity and low computation requirement offered by the EQL GRA that generally operates on the frequency-domain method. As a result, conservative results provided by EQL GRA is for mostly used for amplification based designs while the nonlinear GRA is mainly used to conduct intricate soil structure interactions of foundations and their responses. As the urbanization of Itanagar city for the smart city is impending, the authors believe that the current findings are can be more oriented in providing a design perspective to the region and, hence, EQL GRA is used in the present study. Once the designs are decided, the responses of the actual structures can be further studied through a more intricate nonlinear GRA. In this regard, it is worthwhile to mention that the importance of performing EQL and its application towards the design of earthquake resistant structures has been reported by many earlier researchers [4-7].

According to Ranjan [8], the EQL based GRA of the Dehradun city revealed that the spectral acceleration varied between 0.06g-0.37g at frequency range 1-10 Hz. Interpolation technique in a GIS platform was used to create spectral acceleration maps of the city for frequencies of 3 Hz, 5 Hz, and 10 Hz, which indicated the vulnerability of structures during earthquakes. Thaker et al. [9] conducted the EQL-based GRA for the Kutch region, Gujarat, with the aid of DEEPSOIL and SHAKE (2000). In response to Peak Bedrock Acceleration (PBRA) of 0.088g), the Peak Ground Acceleration (PGA) at the surface level was observed to be 0.216g, thereby showing that the soils of the Kutch region have significant potential to amplify the input seismic motions. For Imphal city of Manipur, Pallav et al. [10] used the non-linear GRA employing SHAKE 99. Based on all the synthetic seismic events, the mean and standard deviation of surface level spectral ground acceleration at PGA and natural periods of 0.3 s and 1 s are presented in the form of contour maps [10]. For Kolkata metropolitan district, Roy and Sahu [11] used an EQL approach using SHAKE (2000). The PGA was observed to be in a range of 0.169g to 0.414g, while the maximum amplification factor ranged from 2.2 to 3. Naik and Choudhury [12] have studied GRA for the territory of Goa; EQL was adopted for conducting GRA using DEEPSOIL. For the same earthquake motion, the PGA-based amplification factors differed from site to site within a range from 1.56 to 2.36. Kumar et al. [13] used DEEPSOIL for conducting the GRA of Guwahati city by employing both the EQL and NL approaches. The results of both EQL and NL analyses shows that stiffer soil layers yield similar PGAs. For Mumbai city, DEEPSOIL was used for conducting EQL and NL GRA. Seismic amplification was observed to vary between 2.53 to 4.14 for frequency ranges from 1.75 Hz to 3.5 Hz [14]. Pandey et al. [15] used SHAKE2000 for conducting EQL GRA in Uttarakhand, India. For different sites, the site amplification ratio varied from 2.5 to 4.9, and the normalized response spectrum obtained from GRA differed significantly from that obtained from IS1893-2016 [16]. Ahmad and Bhattacharjee [17] adopted the non-linear GRA method using DEEPSOIL for

Jorhat City, Assam. The results revealed that the PGA values between varied in the range of 0.13-0.19g and amplification ratios varied between 1.04 and 1.37. Basu et al [18] have found out that the equivalent linear analysis overestimates the ground response parameters as compared to those obtained from nonlinear approach, the overestimation being substantial for high PBRA input motions. EQL approach induces more seismic energy into the system and thus results in elevated PGA, spectral ratios and shear stress ratios. EERA software was used by Sil and Haloi [19] to estimate EQL ground motion parameters for Silchar city, where given the subsurface stratigraphy, the soil conditions are very likely to modify the ground motion parameters. Amplification of peak bedrock amplification up to 4.6 times was observed within the frequency range of 2-8 Hz. Dammala et al. [20] used DEEPSOIL and adopted the nonlinear effective stress analysis for the Northeast region. As a result of high strains induced within the soil, seismic waves in the surface stratum were found to be attenuated for PBRA greater than 0.1g, while surface amplification was observed for ground motions with PBRA lesser than 0.1g. Basu et al [18] stated that ground response parameters depend on the soil properties like shear wave velocity, depth of water table as well as on the input motion characteristics like peak bedrock level acceleration amplitude and frequency content. Yildiz [21] have carried out seismic site characterization of Battalgazi in Malatya, Turkey. Both EQL and NL approach is used to carry out ground response analysis. The results revealed that the surface responses were significantly amplified (i.e., up to 7.5g) in regions where alluvial units are deposited and deamplifed (i.e., 0.94g or lesser) in the regions where mostly volcanic rocks are deposited. For Amravati Region in Andhra Pradesh, Reddy et al. [22] have implemented EQL methods for conducting GRA using DEEPSOIL. The estimated PGA varied from 0.19g to 0.26g, and the acceleration of the amplification range varied from 2.37 to 3.25 for the region. Using DEEPSOIL, Mase et al. [23] conducted EQL seismic GRA for Bengkulu City, Indonesia. In comparison with the bedrock input motion, the PGA at the ground surface is observed to be relatively higher. As a result of a study of this area, peak ground acceleration ranged between 0.2-0.8g, while spectral acceleration varied between 0.5-1.5g and 0.4-0.8g for periods of 0.2 s and 1 s, respectively. The site amplification factors ranged from 0.5 to 1.6. Nonlinear GRA was conducted by Pawirodikromo [24] for Yogyakarta region in Indonesia to find the causes of damages of building. It was found out that the high level of ground shaking and amplification was primarily responsible for the damages in the buildings of the region. At ground surface, PGA ranged from 0.4g to 0.412g. There was a significant site amplification of seismic waves which was observed to vary between 1.40-1.426. Using PLAXIS software, Kumar et al. [25] performed EQL and nonlinear analyses in Kalyani region, AIIMS Kolkata. Compared to NL-based GRA, EQL analyses provided conservative results. EQL and NL analyses indicated that simplified methods fail to predict liquefaction susceptibility in certain regions.

Itanagar city, the capital of the state of Arunachal Pradesh, India, is one of the most prominent cities of the North-east region of India. In 2018, the State for Housing and Urban Affair had added Itanagar region to the Smart City list. Itanagar city is experiencing a growing importance and an ever-shifting urban dynamics as well as land use pattern. This region falls under seismic Zone V, the highest seismic zone in the country having a macrozonation factor of 0.36 [26]. Given the potential of damage which can be incurred by a devastating seismic event, it is very crucial to perform GRA of the region to intricately comprehend the potential amplification of bedrock motion at the ground surface. This would largely help in designing the earthquake resistant structures, while at the same time, aid in assessing the seismic health of the existing important structures and their required retrofitting for enhancing their life period with the ever changing tectonic and seismic scenario of North-East India. Although it is found that GRA has been conducted for many of the Indian cities as well as for various cities over the world, yet to the best of the authors' knowledge, no literature has been compiled or found available for the Itanagar city. There exists a significant gap in the research related to the seismic response of this region, and hence, a comprehensive GRA should be conducted to understand the potential vulnerability of this region. This paper aims to investigate the site response of Itanagar region (Arunachal Pradesh, India) and analyse the ground motion parameters to enhance the understanding of seismic behaviour of the region. This study aims to assess the influence of local soil conditions of this region on the response of the ground by using DEEPSOIL, a computer program developed to perform EQL ground response analyses based on the input of soil data. A key objective of this study is to provide valuable insights into engineering practices and urban planning by analysing geological data, conducting field investigations, and utilizing advanced computational techniques.

## 2. Study Area and its Seismicity

Figure 1 depicts the study area in Itanagar, situated in North-Eastern state of Arunachal Pradesh, India. It also shows the seismicity of this region and its tectonic setting. The town centre is located at coordinates 27°05'54" N and 93°37'19" E. Itanagar, the capital city of Arunachal Pradesh, is positioned within the Himalayan Fold Thrust Belt, which is an active seismotectonic zone adjacent to the plate boundary. This region falls under Zone V, denoting the highest level of seismic vulnerability according to the classification available in the Indian Standard Code IS1893-

2016 [16]. Arunachal Pradesh, spanning an area of 83,743 $km^2$, is situated in the northeastern part of India. It is a physiographic division of the expansive Himalayan Mountain range. The state is characterized by several significant rivers, including Lohit, Dibang, Siang, Kameng, and Subansiri, which are known for their considerable influence within the region. The seismicity of eastern Himalaya is considered to be due to the collision between the Indian plate and Eurasian plate. Northeastern region has been divided into four Seismotectonic domains (Seismotectonic atlas, GSI [26]). In the Eastern Himalayan Fold Thrust belt, there are a number of regional thrusts that strike east-west and follow a southward trend such as the Main Central thrust (MCT), the Main Boundary thrust (MBT), and the Main Frontal thrust (MFT). Continued southward advancement of these sheets over the Indian shield along the southern Himalayan thrust front, by a strike slip mechanism, has resulted in inter-seismic strain accumulation and episodic co-seismic strain release [27]. The southern part of the Shillong massif is demarcated by the Dauki Fault which has records of earthquake events having magnitude as high as $M_w7$. The Mikir Hills and the uplifted Shillong Plateau lies in the south of the Eastern Himalaya and the alluvial-covered foredeep formed by the down warping of the Indian shield basement. The Shillong plateau and Mikir Hills have witnessed a number of tectonic uplifts at least since the early Tertiary period [28, 29].

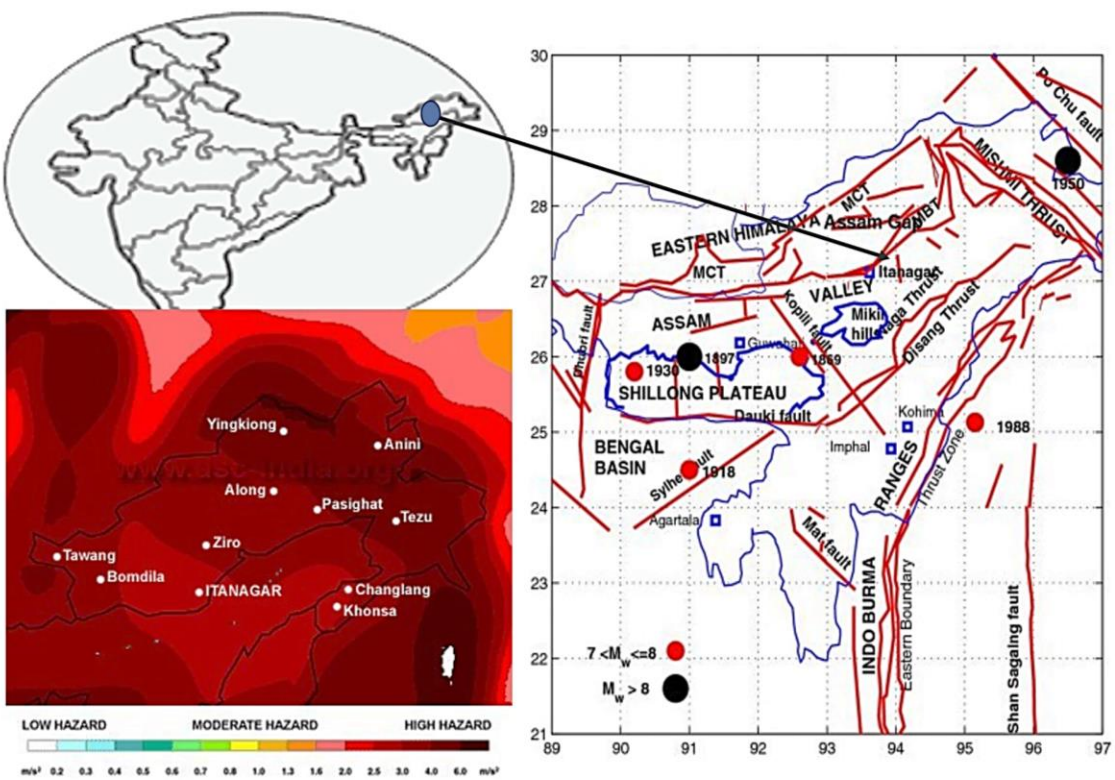


**Fig. 1** Location of Itanagar, Arunachal Pradesh and its seismotectonicity (Adapted from [27])

## 3. Methodology

Ground Response Analysis (GRA) is adopted to determine the site response of Itanagar region. The term "GRA" is used to describe a variety of ground response analysis techniques, including one-dimensional, two-dimensional, and three-dimensional approaches. In the present study, equivalent linear (EQL) based GRA is used to assess the parameters of interest that includes the fundamental frequency of the substrata, amplification factor and response spectra. The results of this study would be useful for the safe and sustainable design of structures in the areas prone to seismic hazard, and even for the evaluation of seismic health of the existing structures.

### 3.1 *Equivalent Linear (EQL) Ground Response Analysis (GRA)*

Equivalent linear (EQL) analysis is a method used to conduct ground response analysis for assessing the response of the subsurface subjected to seismic loading. It is based on the assumption that the soil can be represented as a linear Kelvin-Voigt (KV) viscoelastic system with a constant shear stiffness and damping coefficient [4]. Based on the assumption of vertical propagation of shear waves through the KV element, Eqn. (1) describes the stress-strain behavior during shearing.

$$\tau = G\gamma + \eta \frac{\partial \gamma}{\partial t} \qquad (1)$$

where, $\tau$, $\eta$, $\gamma$ (=$\partial u/\partial t$) and $G$ are the shear stress, the coefficient of viscous damping, shear strain and shear modulus, respectively. Shear waves propagating vertically (in z-direction) can be described by the one-dimensional equation of motion as

$$\rho \frac{\partial^2 u}{\partial t^2} = \frac{\partial \tau}{\partial z} \qquad (2)$$

By substituting Eqn. (1) into Eqn. (2), the equation of motion under shearing can be expressed as

$$\rho \frac{\partial^2 u}{\partial t^2} = G \frac{\partial^2 u}{\partial z^2} + \eta \frac{\partial^3 u}{\partial z^2 \partial t} \qquad (3)$$

where, $\rho$ represents mass density of the medium and $u$ represents displacement along the lateral direction. The one-dimensional ground response is obtained by solving Eqn. (3).

In this study, the EQL method of analysis is implemented through the DEEPSOIL program. The primary constitutive model in DEEPSOIL follows the hyperbolic model developed by Konder and Zelasko [30] that was suitably modified by Matasovic and Vucetic [31]. In the present study, the pressure-dependent hyperbolic model (MKZ) with hysteretic behaviour using Masing rules is utilized for all the soil layers. In order to characterize the shear stiffness of the soil, the shear wave velocity is used as an input parameter. The modulus reduction ($G/G_{max}$) and damping ratio ($\xi$) curves are defined as functions of the shear strain. For clayey soils, the standard modulus reduction and damping ratio curves proposed by Vucetic and Dobry [32] are utilized, while for sandy soils, the standard curves proposed by Seed and Idriss [2] are employed to define the strain-dependent dynamic properties. For modelling purpose, all boreholes are assumed to have bedrock or a very stiff soil layer at the bottom, represented by a rigid half-space which does not participate in modifying the propagating seismic wave.

After the analysis is completed, the results are analysed to understand the ground response. DEEPSOIL provides various output options, including time histories of displacements, velocities, and accelerations at different depths in the soil layers. Based on the results of the ground response analysis, engineers and researchers can interpret the behaviour of the soil layers during the seismic event and make informed decisions in designing structures and mitigating seismic hazards. Figure 2 shows the dynamic models using a spring-mass-damper system. To model the ground response using the spring-mass-damper system, the soil profile is divided into layers, each represented by a spring, mass, and damper. The stiffness of the springs is determined based on the soil's shear modulus, which can be estimated from laboratory tests or empirical correlations. The masses represent the inertia of the soil layers, while the dampers account for energy dissipation due to damping. Once the ground is modelled using the spring-mass-damper system, dynamic analysis techniques can be employed to study its response to seismic loading. The response is typically evaluated in terms of acceleration, velocity, and displacement. Various numerical methods, such as time history analysis or response spectrum analysis, can be used to calculate the ground response.

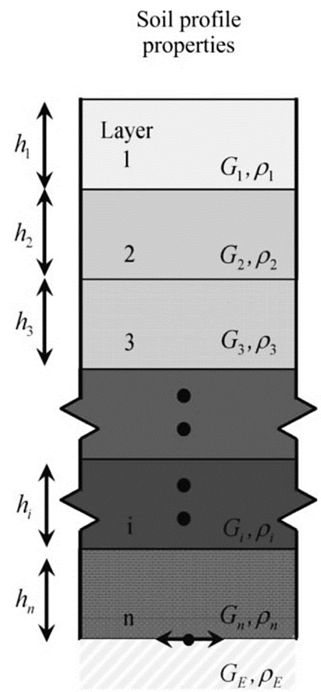


**Fig. 2** Soil model utilizing stiffness and damping parameters for site-response analysis

The EQL method is used to conduct site response analysis at specific locations within Itanagar region. Seismicity information and geotechnical data were collected from designated study regions. Considering each of the subsurface stratum as a linear viscoelastic system, the frequency domain analysis adopted in EQL approach assumes that the shear modulus and damping coefficient are constant and independent of strain level. Hence, based on the obtained shear strain histories for each layer, an iterative approach is used to estimate the compatible nonlinear strain dependent dynamic soil properties. An initial estimate of damping and modulus values is used to assess the strain-time histories generated within each soil layer by the propagating strong motion. By analyzing the strain-time histories for each layer, the maximum shear strain is identified, which is further used to estimate the effective shear strain. Kramer [4] suggests that the effective shear strain should be 65% of the maximum shear strain generated in a layer. According to Idriss and Sun [33], the shear strain ratio (SSR, i.e. the ratio between the effective shear strain and the maximum shear strain generated) is based on the earthquake magnitude (*M*) as expressed in Eqn. (4).

$$SSR = \frac{M-1}{10} \tag{4}$$

Corresponding to the evaluated effective shear strain in a given soil layer, a strain-compatible shear modulus and damping ratio is determined, which, along with small-strain shear modulus and damping, is further used to obtain the stress-strain-time estimates in the next iterative cycle. After repeated iterations, a convergent solution of strain compatible shear modulus and damping ratio is obtained. The shear modulus represents the secant shear stiffness, while the damping ratio represents energy absorption or dissipation prevalent in a soil layer undergoing a specific strain. This procedure of EQL analysis aids in a convenient assessment of ground response with computational ease.

### 3.2 *Geotechnical Site Characterizations*

The geotechnical data used in this study were sourced from available bore-logs specific to the study region. These borelogs were obtained from the different public and government departments of Itanagar region associated with construction and urban planning sectors. As shown in Fig. 3, a total of seven boreholes, each in the locations of CM residence, MOWB-II, VIP Housing, Raj Bhawan, Secretariat, Itafort, and State Assembly were selected for analysis. Figure 4 presents the borehole profiles from the locations of VIP housing, Secretariat, State assembly, CM residence, MOWB-II, Itafort and Raj Bhawan, where the soil is predominantly classified as Poorly graded sand (SP), Poorly graded sand and gravels (SP-GP), Medium plastic inorganic clay (CI), Clayey Sand (SC) and Sand with silty fines (SM) as per IS1498:1970 [34]. Most of the soil in the considered locations are composed of fine grain sand, light brownish to tan coloured silty clay, along with poorly graded, gritty and cohesionless materials. The soils being mostly cohesionless, the liquid and plastic limits of the soils were not existent. All the locations had soil densities ranging from 1.59-2.1 g/cc. Ground water levels were not observed at any borehole site.

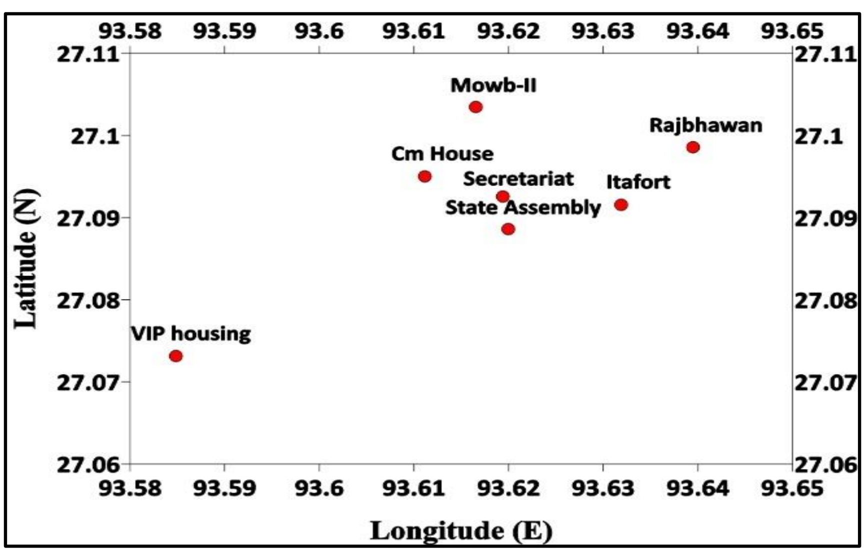


**Fig. 3** Locations of boreholes chosen for the GRA studies in terms of degree northings and eastings

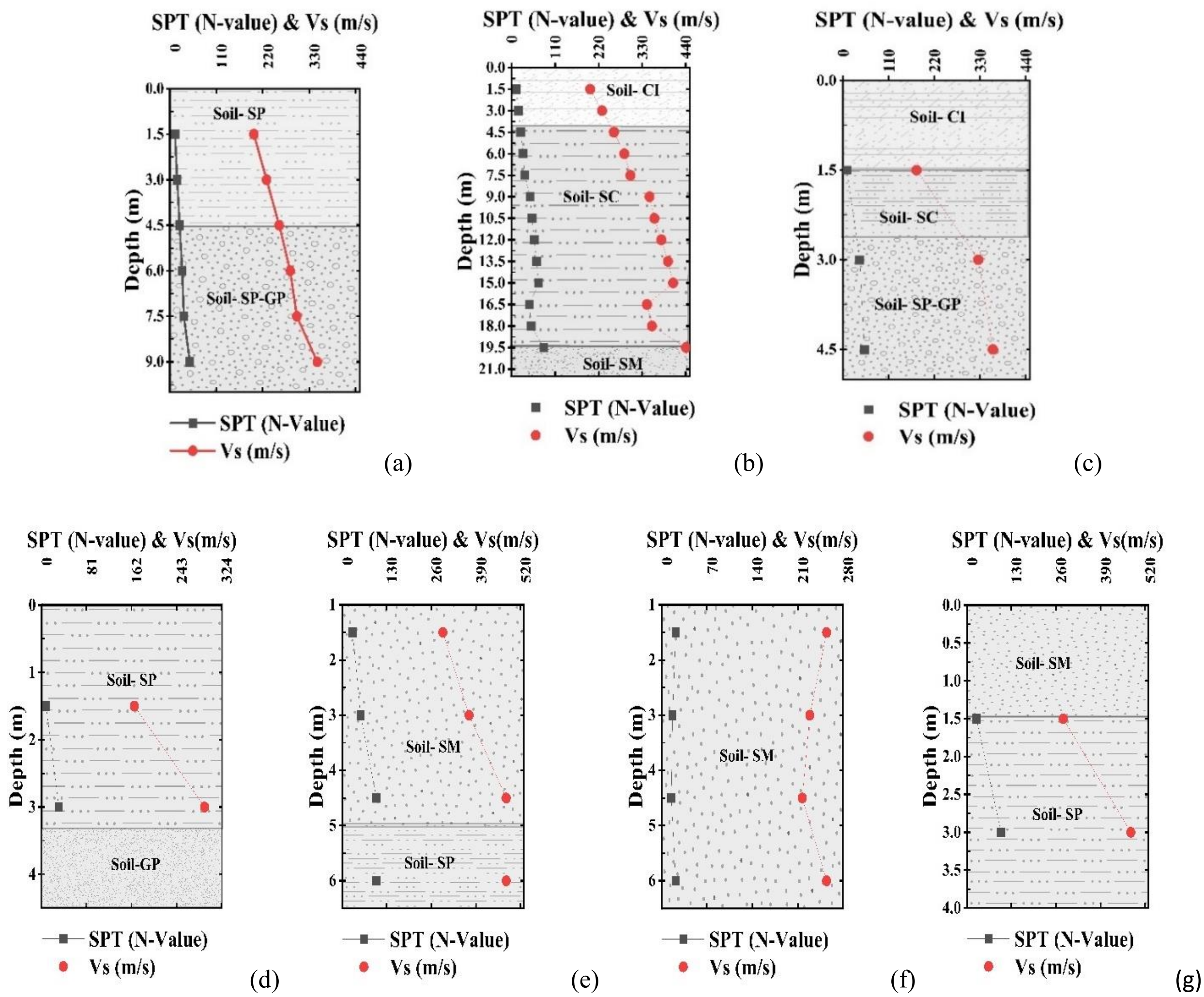


**Fig. 4** Typical borehole profiles from (a) VIP Housing (b) Secretariat (c) State assembly (d) CM Residence (e) Mowb-II (f) Itafort (g) Raj Bhawan

The correlation between $V_s$ and SPT-N is very limited for North-East India [35]. Hence, for Itanagar city of Arunachal Pradesh, it is important to acquire the shear wave velocity profile of different locations which can be further used as input for the GRA using DEEPSOIL. As there were no direct estimation or geophysical-based assessments of the shear wave velocity ($V_s$) profiles for the concerned locations, the same had to be indirectly assessed based on borehole stratigraphy. In order to achieve this, 22 empirical correlations between SPT-N values and shear wave velocity were used that are developed by different researchers. As the empirical formulations were solely dependent on N-value, it is considered that they are tentatively applicable to various types of soils. Hence, with the aid of linear regression analysis, for each of the earlier stated borehole locations in the Itanagar city considered in the present study, the shear wave velocity ($V_s$) profile is determined by formulating an empirical correlation with the Standard Penetration Test (SPT) N-value for the corresponding location. As a typical example, considering the SPT-N values obtained from the Secretariat site (Fig. 4b), Fig. 5 illustrates the $V_s$ profile obtained by using each of the 22 empirical correlations from different researchers [36-56]. Further, an average $V_s$ profile along the depth (obtained as average of the 22 $V_s$ profiles) is obtained which is expressed as:

$$Vs = 70.289N^{0.4164} \quad (5)$$

Based on Eqn. (5), $V_s$ profiles for each site were generated using the corresponding SPT-N values recorded from the borehole investigations. This regression relation has yielded a correlation coefficient $R^2$ value of 0.9997, which indicates a superior confidence on the obtained results. The $V_s$ profiles were then used to estimate the shear modulus reduction and damping ratio curves which were further utilized for conducting the GRA.

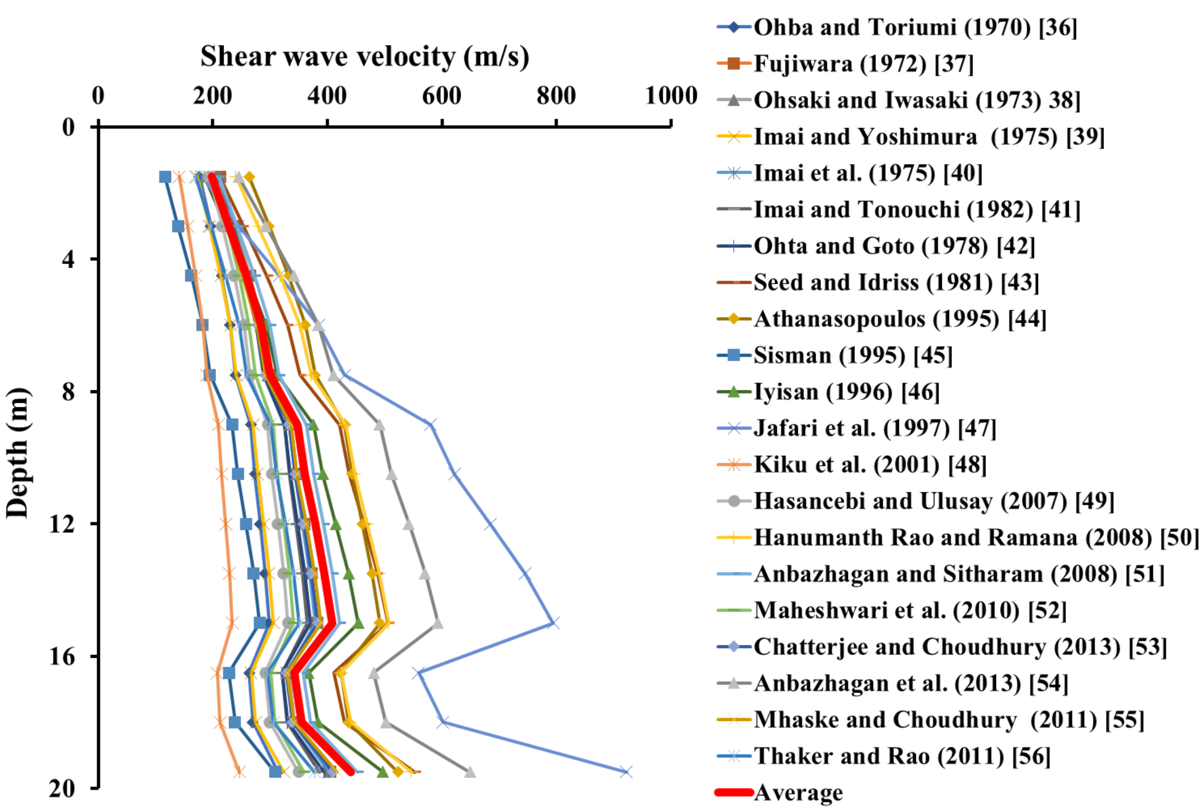


**Fig. 5** Development of shear wave velocity profile for the Secretariat location and formulation of an empirical correlation between $V_s$ and SPT-N value for Itanagar city, Arunachal Pradesh

### 3.3 *Acceleration-time history*

Acceleration-time history, which contains the distribution of seismic energy over time, is one of the essential input parameters to perform seismic GRA. Based on the seismic zonation reported by IS1893-2016 [16] as well as from the prevalent seismicity of Itanagar (Arunachal Pradesh), it can be stated that the entire Arunachal Pradesh region comes under the seismic Zone V. Therefore, to design the earthquake resistant structures, the selection of acceleration-time histories in earthquake prone area is quite a challenging task. For the design earthquake resistant structures, based on the maximum considered earthquakes (MCEs) and the design basis earthquakes (DBEs), IS1893-2016 [16] has recommended the design value of PGA = 0.36g and 0.18g, respectively. Therefore, considering the seismicity of the study region and the recommended PGA by IS1893-2016 [16], five different earthquake motions of different PGA are chosen as input acceleration-time histories. The PGA of Coyote EQ (1979, $M_w$5.7), Kocaeli EQ (1999, $M_w$7.4), Loma Gilroy-2 EQ (1989, $M_w$6.9), Mammoth Lake EQ (1980, $M_w$4.9) and Kobe EQ (1995, $M_w$6.9) strong motion is 0.12g, 0.22g, 0.36g, 0.43g and 0.82g, respectively, thereby considering low to very high seismic intensity of earthquakes in the ground response analysis. These strong motion records are obtained from the database of DEEPSOIL software. Figure 6 presents the acceleration-time histories and the Fourier amplitude spectrum of all five input motions. The fundamental frequency band of input motion was found to be in the range of 1.42 - 5.35 Hz. Further, using Seismosoft [57], the strong motion characteristics such as arias intensity, $V_{max}/A_{max}$, predominant period, mean period, bracketed duration and significant duration are derived and are shown in Table 1. It can be observed that the average period of strong ground motions varied between 0.3s and 0.65s.

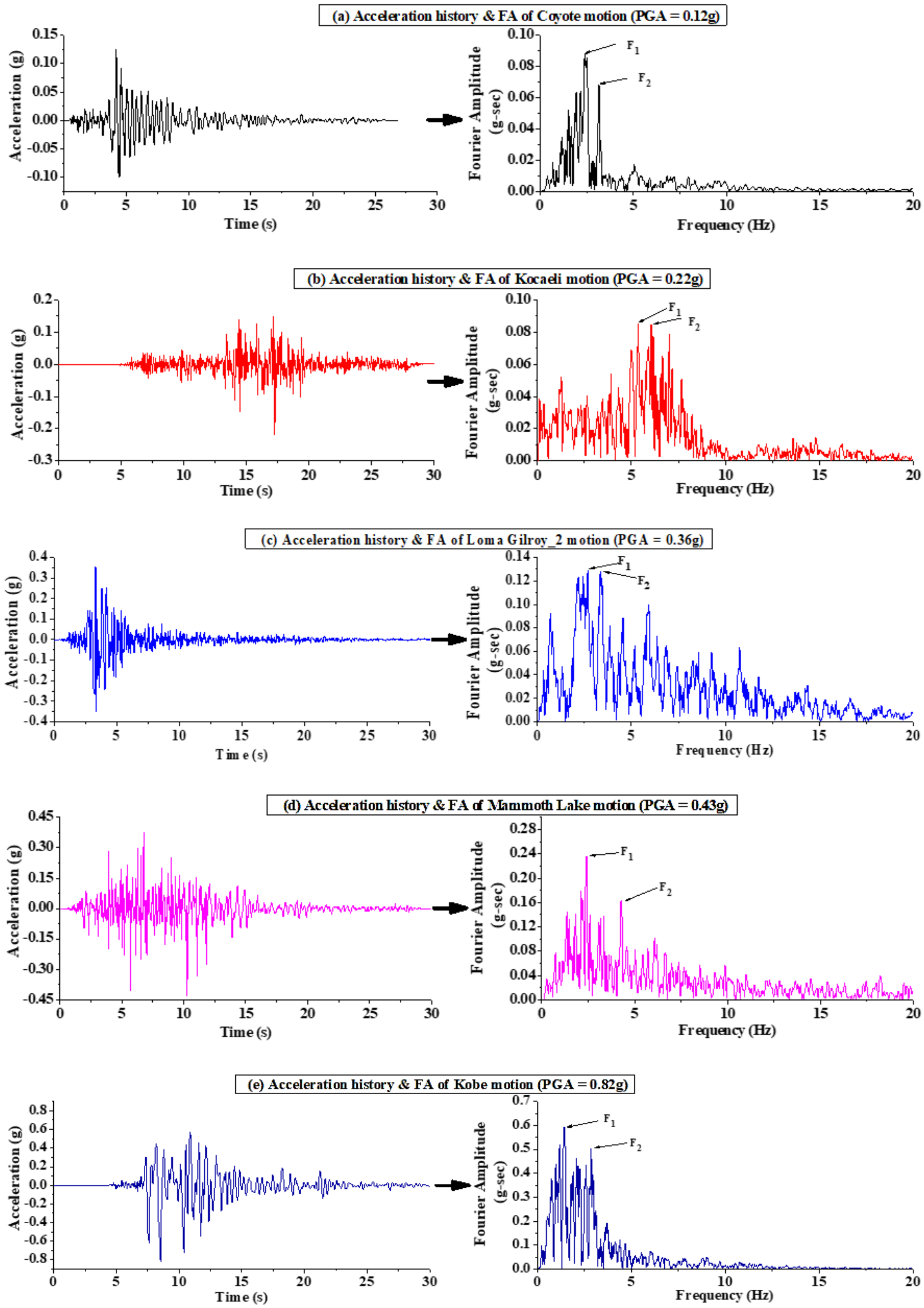


**Fig. 6** Acceleration-time history of input motion and their Fourier amplitude

**Table 1** Parameters for strong motions for different earthquakes

| Strong motion parameters | Coyote (1979) | Kocaeli (1999) | Loma Gilroy-2 (1989) | Mammoth Lake (1980) | Kobe (1995) |
|---|---|---|---|---|---|
| Date | 06-08-79 | 17-08-99 | 18-10-89 | 27-05-80 | 17-01-95 |
| Magnitude ($M_w$) | 5.7 | 7.4 | 6.9 | 4.9 | 6.9 |
| PGA (g) | 0.12 | 0.22 | 0.36 | 0.43 | 0.82 |
| Predominant period (sec) | 0.42 | 0.16 | 0.40 | 0.16 | 0.36 |
| Mean period (sec) | 0.457 | 0.306 | 0.365 | 0.371 | 0.649 |
| Bracketed duration (sec) | 18.01 | 22.3 | 18.42 | 25.79 | 21.45 |
| Significant duration (sec) | 6.91 | 11.01 | 5.00 | 10.95 | 8.34 |
| Arias intensity (m/sec) | 0.121 | 0.289 | 0.903 | 1.322 | 8.302 |
| Specific energy density ($cm^2$/sec) | 47.03 | 487.62 | 414.52 | 468.88 | 7589.83 |
| Cumulative absolute velocity (cm/sec) | 247.43 | 406.86 | 587.47 | 907.99 | 2076.92 |
| $V_{max}/A_{max}$ (sec) | 0.0628 | 0.0824 | 0.0820 | 0.0560 | 0.1010 |

## 4. Results and Discussions

Results obtained from equivalent linear seismic GRA, subjected to five different input acceleration-time histories, are presented in terms of the variations of acceleration with depth, amplification/ deamplification seismic waves, spectral acceleration (SA) at surface level, variations of strain and shear stress ratio for Itanagar region.

### 4.1 *Influence of local soil conditions on GRA of Itanagar city*

This section presents the variation of peak horizontal acceleration, amplification or deamplification of seismic wave, peak horizontal displacement, peak strain and peak shear stress ratio along with depth for the bedrock PGA 0.12g, 0.22g, 0.36g, 0.43g and 0.82g corresponding to the Coyote EQ ($M_w$5.7), Kocaeli EQ ($M_w$7.4), Loma Gilroy-2 EQ ($M_w$6.9), Mammoth Lake EQ ($M_w$4.9) and Kobe EQ ($M_w$6.9), respectively. Subjected to the 1979 Coyote strong motion having a PGA = 0.12g, Figures 7(a-e) present the results obtained from equivalent linear GRA to exhibit the influence of site-specific substrata on the response entities of various locations chosen for the present study.

Figure 7a presents the variations of peak horizontal acceleration with depth at different borehole locations, which indicates that each soil site responds in a unique way during earthquakes depending on soil type as well as soil conditions. The variation of acceleration corresponding to the secretariat site is found to be comparatively higher than the other sites. It is observed that the secretariat site consists of predominantly clayey and silty soil, which is responsible for the high amplification of seismic wave. It can also be seen that the free field PGA at surface level was found be in the range of 0.218g to 0.326g subjected to input motion of PGA = 0.12g, which is an indication of the amplification of seismic wave. The amplification of seismic wave at surface level was found to be in the order of 81.75% to 171.88%, shown in Fig. 7b, indicates the percentage outcome of PGA at surface level with respect to the bedrock PGA. Further, the displacement of ground was found to be in the range of 0.14 mm to 5.3 mm at the surface level, shown in Fig. 7c, which indicates the possibility of ground deformation. This deformation is responsible to develop the shear strain in the ground. The maximum shear strain ($\gamma_{max}$) developed along the depth (Fig. 7d), subjected to the bedrock PGA = 0.12g, is found to be in the range of $0.01\%<\gamma_{max}<0.05\%$. These values of shear strains come under the moderate range of shear strain [58, 59]. The variations of soil stiffness over these range of shear strain are possible to trigger lateral spreading or ground cracking under free field conditions. The degradation in the soil stiffness, especially under the undrained conditions, is mainly due to the development of shear strain within the ground, which is further responsible for the development of stress. If the developed shear stress is greater or less than the shear strength of soil, accordingly the flow liquefaction or cyclic mobility might occur within the ground. Figure 7e shows the variations of the shear stress ratio (i.e., the ratio of shear stress to the overburden stress) with depth at all seven sites, subjected to bedrock PGA = 0.12g. The shear stress ratio at surface level is found to be in the range of 0.19 to 0.28. Further, a contour map of maximum acceleration as well as amplification factor obtained at surface level are presented in Fig. 8 and Fig. 9, respectively, which will be further useful for the structural design in Itanagar region while incorporating the ground motion of PGA = 0.12g.

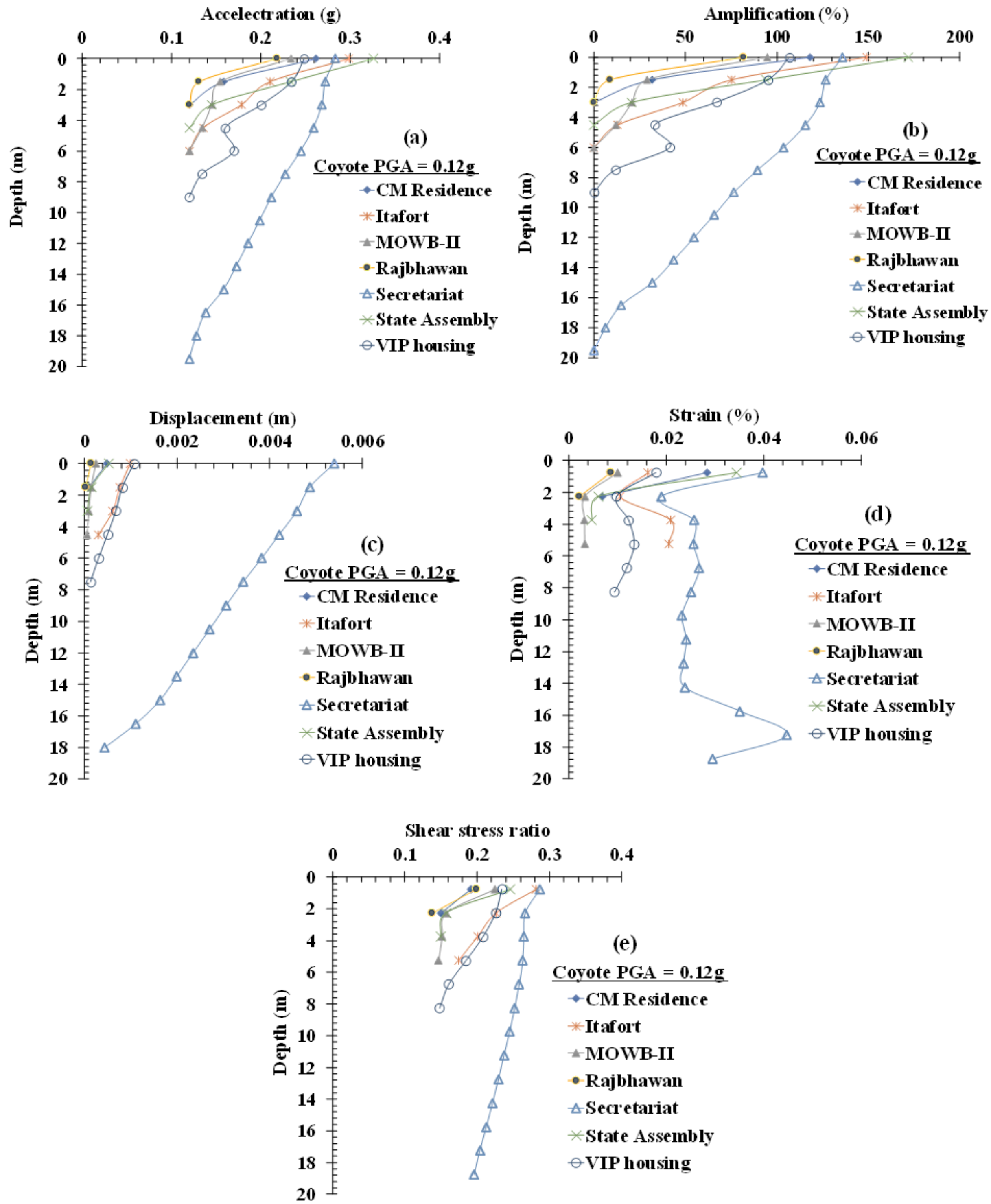


**Fig. 7** Variation of (a) peak horizontal acceleration (b) amplification of seismic wave (c) peak horizontal displacement (d) peak shear strain (e) shear stress ratio along with depth using 1979 Coyote strong motion

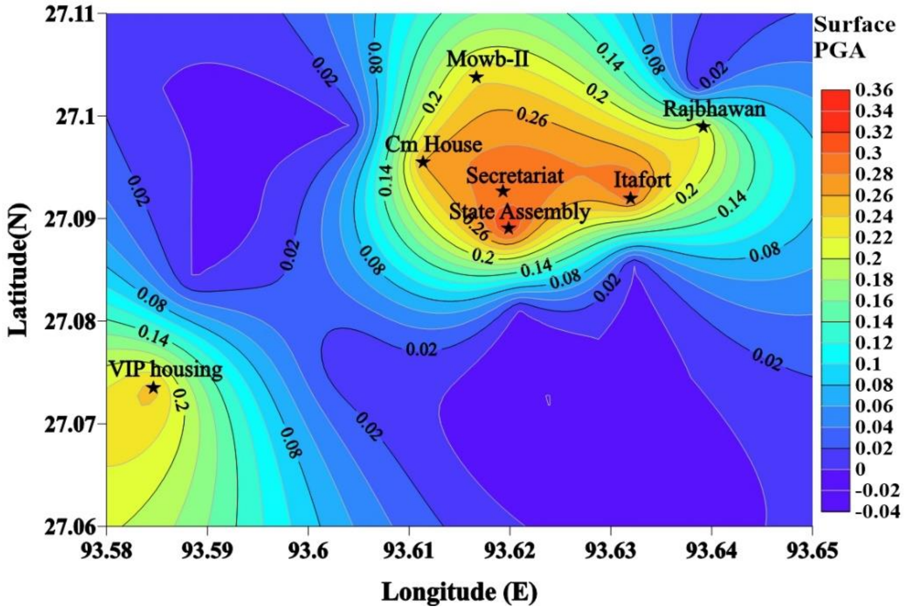


**Fig. 8** Contour map of PGA at ground level in Itanagar region developed from 1979 Coyote motion (PGA 0.12g)

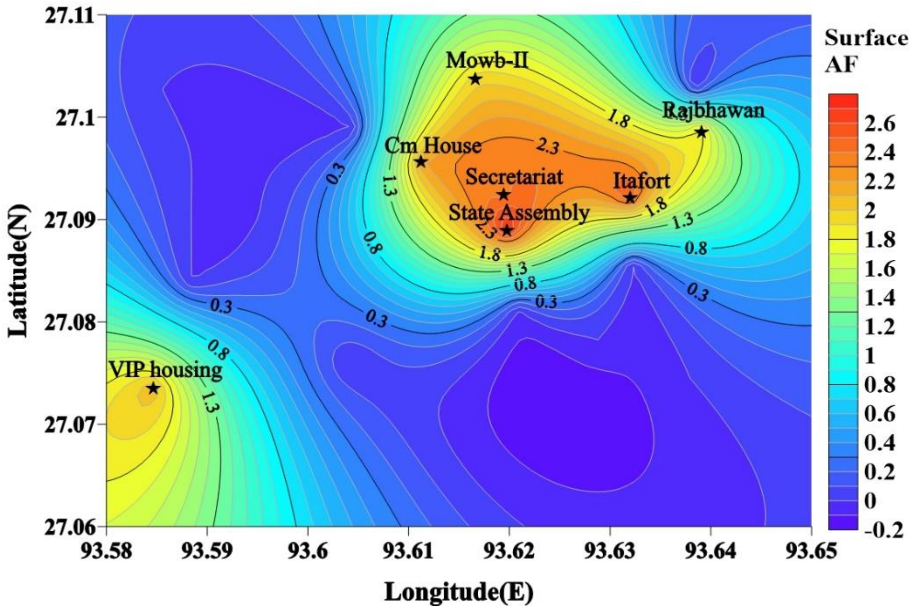


**Fig. 9** Contour map of amplification factor in Itanagar region developed from 1979 Coyote motion (PGA 0.12g)

Further analyses are carried out using Kocaeli EQ motion to observe the impact of high PGA (0.22 g) input motion on the design parameters such as surface acceleration, spectral acceleration, shear strain and shear stress ratio. The maximum acceleration is found to be 0.313g for CM Residence, 0.547g for Itafort, 0.36g for MOWB-II, 0.259g for

Rajbhawan, 0.679g for Secretariat, 0.312g for State Assembly and 0.719g for VIP housing. All these PGA are expectedly higher than that obtained from the input PGA of 0.12 g (as mentioned in the previous section). The amplification of seismic wave at surface level, corresponding to input PGA = 0.22g, is found to be in the order of 17.75% to 227.14%. The deamplification of seismic wave up to 12% is also observed at Secretariat site within the depth of 14 m which can be attributed to the local soil conditions. Further, the ground displacement at the surface level is found to be in range of 0.23 mm to 10 mm and $\gamma_{max}$ is found to be in the range of 0.01% to 0.16% near the surface level. Moreover, the shear stress ratio gradually increases up to surface level and reaches to a limiting range of 0.25-0.67 at surface level. Further, a contour map of maximum acceleration as well as amplification factor obtained at surface level are presented in Fig. 10 and Fig. 11, respectively, which will be further useful for the structural design in Itanagar region while incorporating the ground motion of PGA = 0.22g.

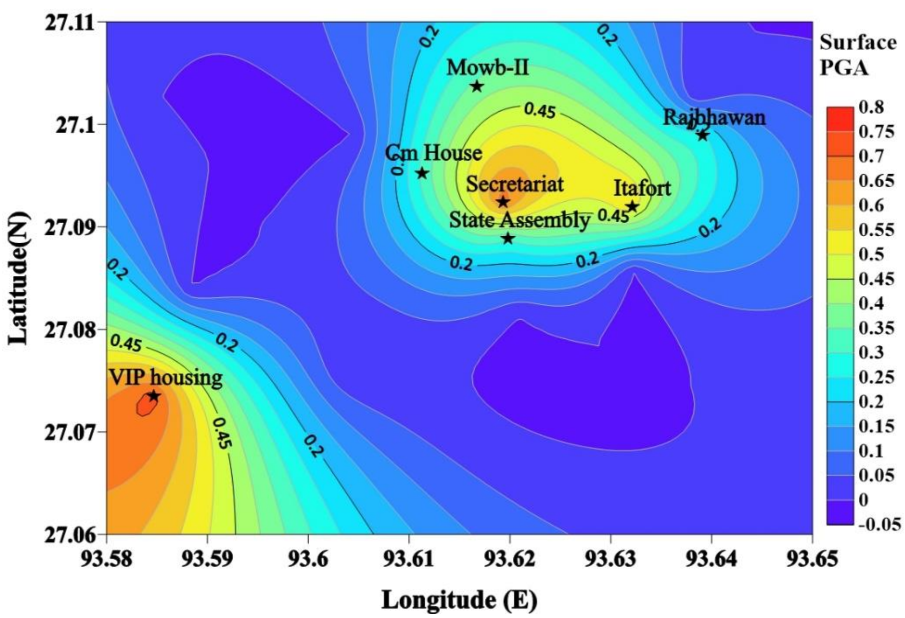


**Fig. 10** Contour map of PGA in Itanagar region developed from 1999 Kocaeli motion (PGA 0.22g)

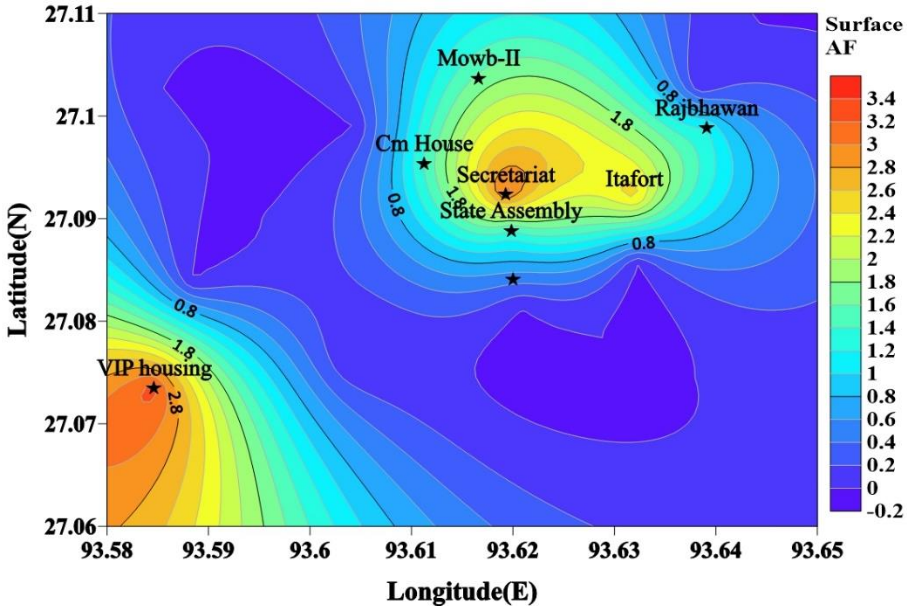


**Fig. 11** Contour map of amplification factor in Itanagar region developed from 1999 Kocaeli motion (PGA 0.22g)

Figure 12(a-e) presents the variation of peak horizontal acceleration, amplification or deamplification of seismic wave, displacement, strain and shear stress ratio along with depth for the bedrock PGA = 0.36g corresponding to Loma Gilroy-2 EQ ($M_w$6.9). From Fig. 12a, it can be observed that the maximum acceleration at surface level is 1.038g, 1.279g, 0.933g, 0.820g, 1.518g, 1.153g and 1.568g for the borehole sites CM Residence, Itafort, MOWB-II, Rajbhawan, Secretariat, State Assembly and VIP housing, respectively, which indicates the amplification of seismic wave from the bedrock location. However, this amplification depends on the soil type and well as the ground motion characteristics. Further, the amplification of input motion of PGA=0.36g is found to be in the range of 127.82% to 335.56%, as shown in Fig.12b. Figure 12c indicates the ground displacement ranging from 0.73 mm to 29.54 mm and $\gamma_{max}$ near the surface level was found in the range of 0.055 to 0.88% (Fig. 12d). Furthermore, the shear stress ratio near the surface is found in the range of 0.77 to 1.43, shown in Fig. 12e, which is comparatively higher than that obtained from input motion of PGA = 0.12g and 0.22g. The variations of maximum acceleration as well as the amplification factor at surface level, in the form of contour map, subjected to input motion of PGA = 0.36g are presented in Fig. 13 and Fig. 14, respectively.

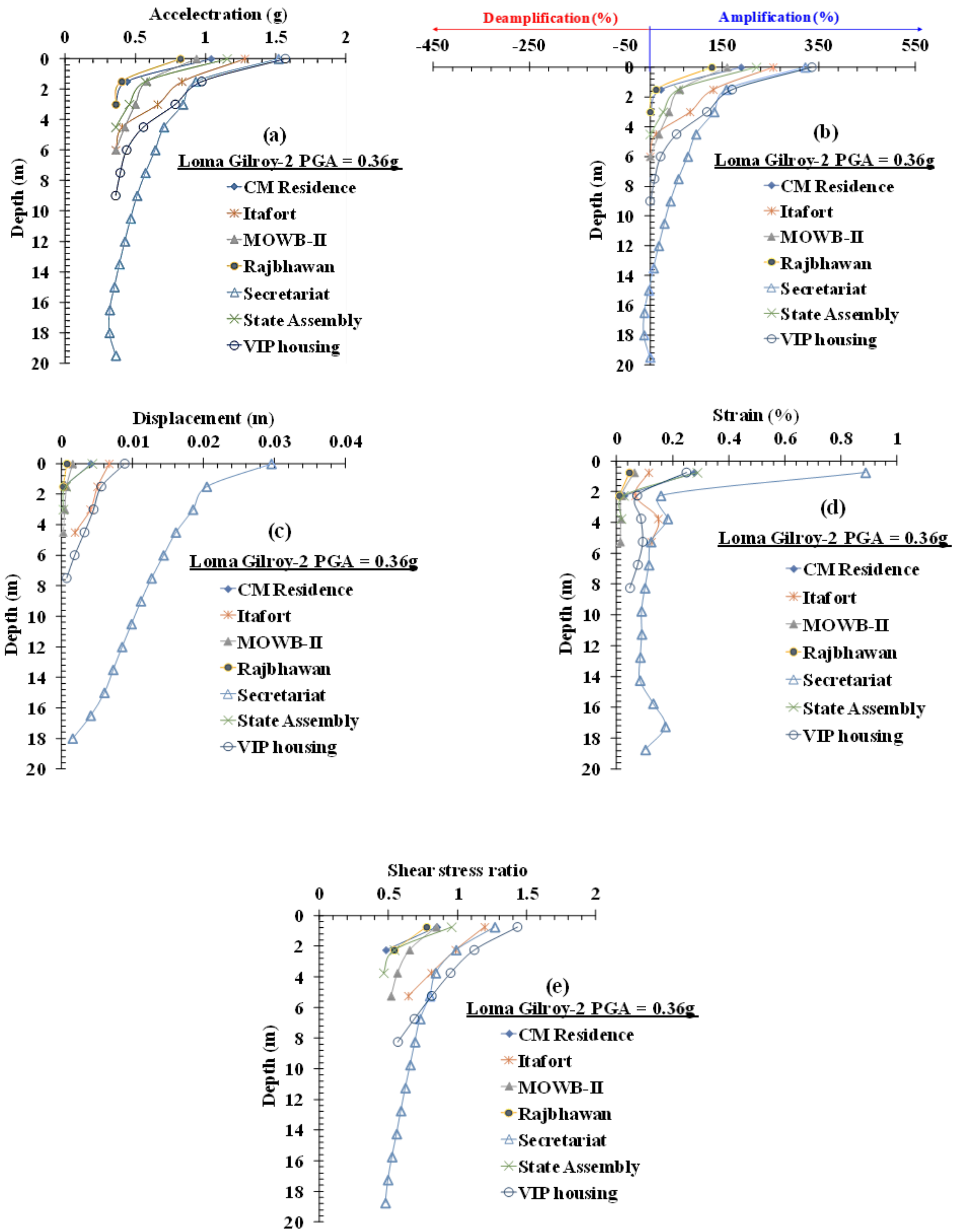


**Fig. 12** Variation of (a) peak horizontal acceleration (b) amplification of seismic wave (c) peak horizontal displacement (d) peak shear strain (e) shear stress ratio along with depth using 1989 Loma Gilroy-2 motion.

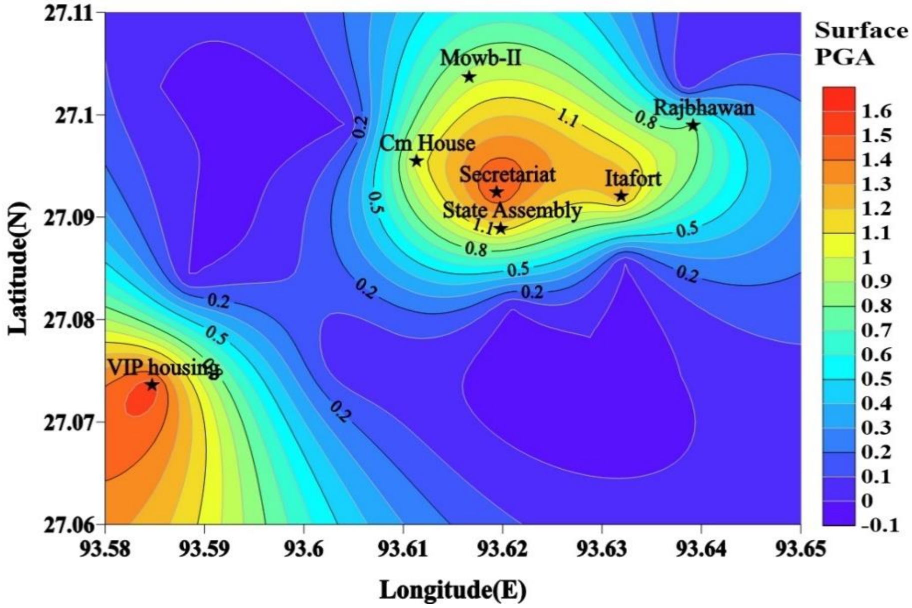


**Fig. 13** Contour map of PGA in Itanagar region developed from 1989 Loma Gilroy-2 motion (0.36g)

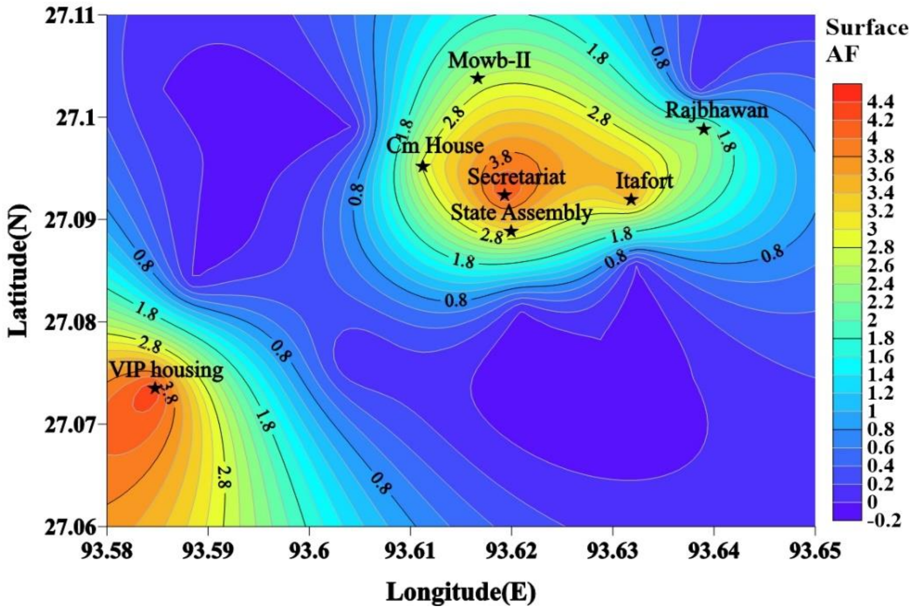


**Fig. 14** Contour map of amplification factor in Itanagar region developed from 1989 Loma Gilroy-2 motion (0.36g)

Seismic ground response analysis is also carried out using Mammoth Lake EQ record as an input motion of PGA = 0.43g. The maximum acceleration at surface level is found to be 0.723g, 0.780g, 1.043g, 0.851g, 0.976g, 0.803g and 1.041g at the site CM Residence, Itafort, MOWB-II, Raj Bhawan, Secretariat, State Assembly, VIP housing, respectively. Moreover, the variations of maximum acceleration at surface level and the amplification factor using EQL analysis for Itanagar region when subjected to severe shaking are presented in the form of contour map in Fig. 15 and Fig.16, respectively. The amplification of seismic wave is found to be in the range of 68.09% to 142.59%. The seismic wave is also deamplified by 8.0% at Secretariat site within the depth of 12 m that might be attributed to local soil conditions. The maximum ground displacement is found to be at surface level in the range of 0.62 mm to 14.78 mm whereas, $\gamma_{max}$ is in the range of 0.04% to 0.34%. The shear stress ratio is observed in the range of 0.45 to 0.85 within the depth of 2.0 m from ground surface.

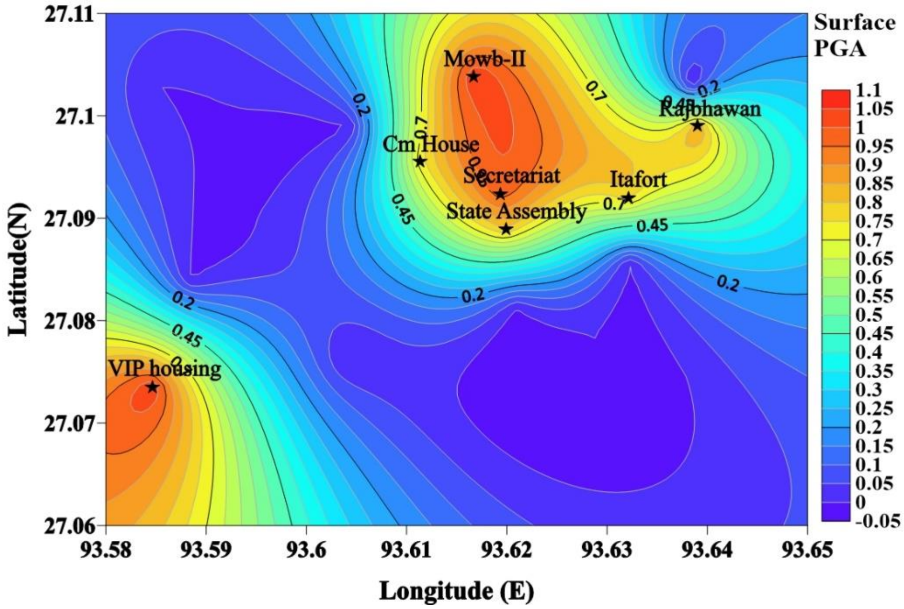


**Fig. 15** Contour map of PGA in Itanagar region developed from 1980 Mammoth Lake motion (0.43g)

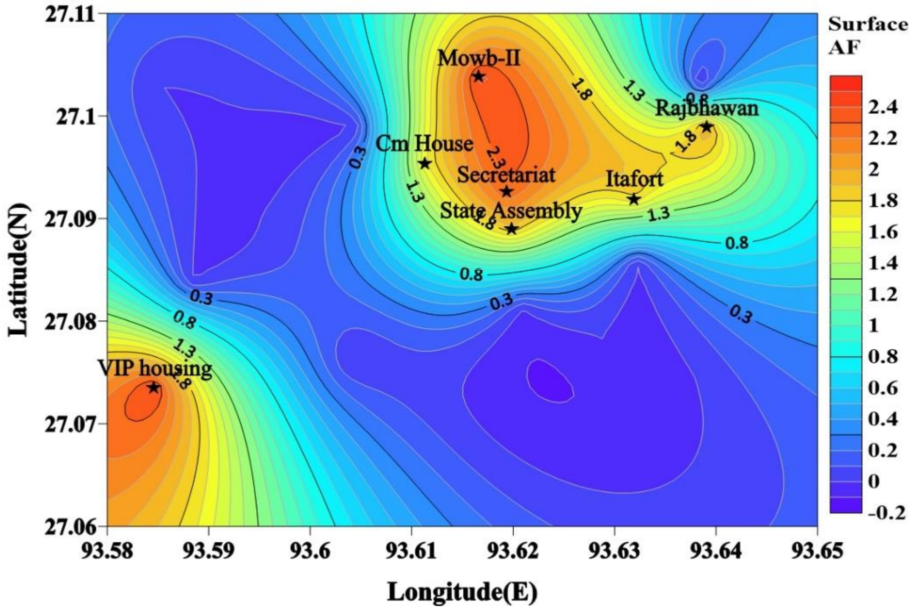


**Fig. 16** Contour map of amplification factor in Itanagar region developed from 1980 Mammoth Lake motion (0.43g)

Figure 17(a-e) present the results of GRA using Kobe EQ motion of PGA = 0.82g, indicating the seismic response subjected to severe ground shaking. During the seismic ground response, the maximum acceleration near the surface level is found to be 0.932g, 1.04g, 0.862g, 0.840g, 1.853g, 0.88g and 1.188g corresponding to the borehole CM Residence, Itafort, MOWB-II, Raj Bhawan, Secretariat, State Assembly and VIP housing, respectively, and the same is presented in Fig.17a. The amplification of Kobe EQ motion of PGA = 0.82g at surface level is found to be in the range of 2.49% to 126.03% (Fig. 17b). Figure 17c presents the ground displacement along with depth and it can be noticed that the maximum ground displacement is in the order of 1.00 mm to 86.9 mm. Further, Fig.17d presents the variations of shear strain with depth and it can be observed that $\gamma_{max}$ is in the range of 0.32% to 1.32%. Figure 17e presents the variations of shear stress ratio along the depth. It can be seen that the maximum value of shear stress ratio is found to be in the range of 0.86 to 1.45. Moreover, the variations of maximum acceleration at surface level and the amplification factor using EQL analysis for Itanagar region when subjected to severe shaking are presented in the form of contour map in Fig. 18 and Fig. 19, respectively.

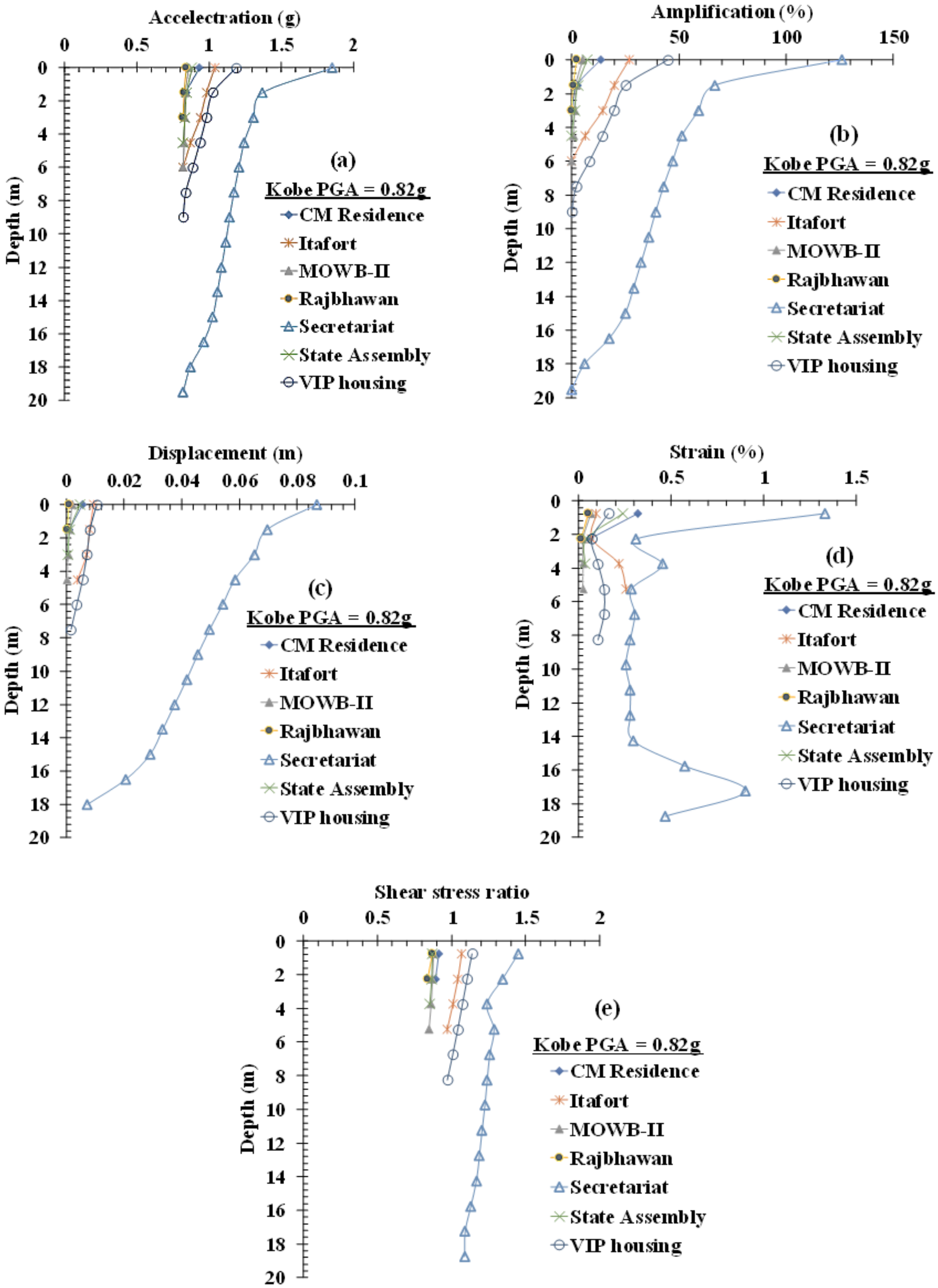


**Fig. 17** Variation of (a) peak horizontal acceleration (b) amplification of seismic wave (c) peak horizontal displacement (d) peak shear strain (e) shear stress ratio along with depth using 1995 Kobe EQ motion

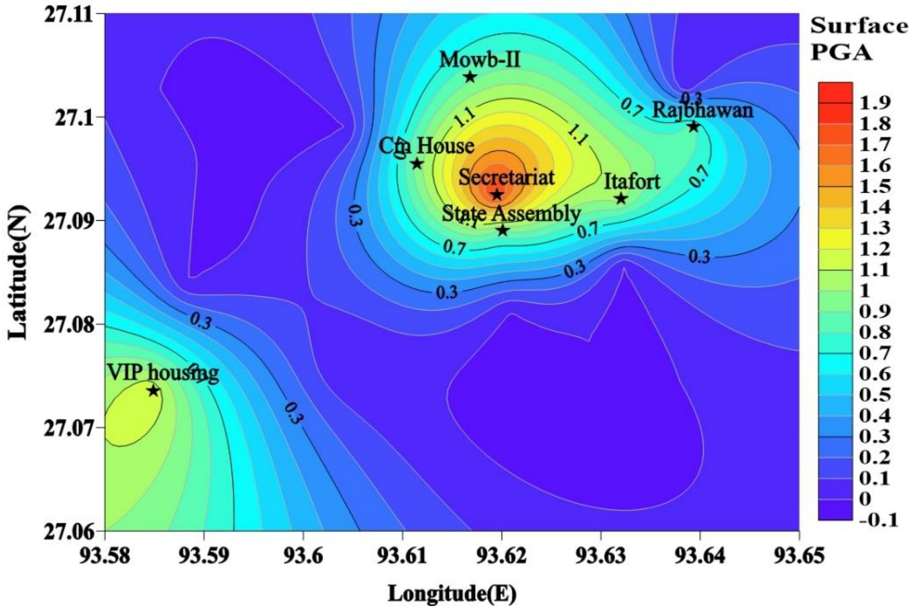


**Fig. 18** Contour map of PGA in Itanagar region developed from 1995 Kobe motion (0.82g)

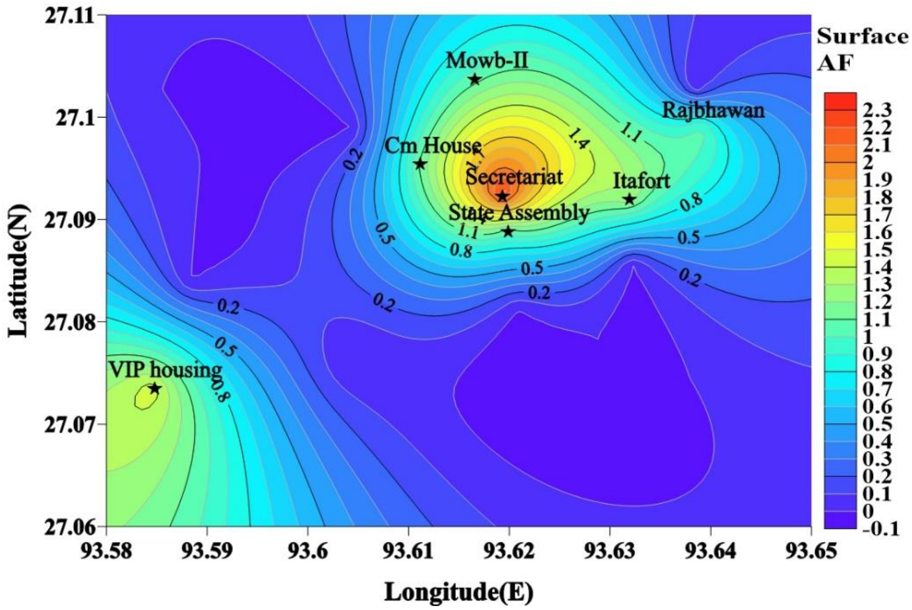


**Fig. 19** Contour map of amplification factor in Itanagar region developed from 1995 Kobe motion (0.82g)

Based on the results presented in Section 4.1, it can be stated that with increasing bedrock PGA , the maximum value of accleration at surface level has increased whereas the amplification factor decreased. It is also observed that there is a deamplification of seismic wave at Secretariat site. The deamplification of waves, at nearly 12 m-14 m depth consisting silty soil with low SPT-N value, might be the indication of soil liquefaction at those specific strata under the action of strong motion. The outcomes are presented in Table 2 in terms of PGA and the amplification factor at the surface level. Table 2 also reflects that the maximum acceleration as well as amplification factor at all seven sites, obtained using Loma Gilroy-2 EQ motion (PGA=0.36g), are comparatevly higher than that obtained from the other input motions, which can be attributed to the effect of ground motion parametres such as significant duration mentioned in the Table 1. Therefore, it can be stated that along with the variations of amplitude parameters (such as input motion PGA), the impact of the other strong motion characetristics such as duration and frequency content parameters over GRA should also be thoroughly studied. Further, it is also found that the ground displacement was increased with increasing PGA of the input motion, which is attributed to the increasing stresses and higher energy propagating through the medium due to higher PGA. It is also found that with the increasing input motion PGA from 0.12g to 0.82g, the shear strain developed within the ground also increased. The development of high value of shear strain i.e., $\gamma_{max} > 0.01\%$ or $\gamma_{max} > 1.0\%$, might be responsible for the catastrophic damage to the ground as well as to the supported structures. Further, the shear stress ratio (ratio of shear stress to the overburden stress) is found to be increased with increasing input motion PGA from 0.12g to 0.82g, primarily due to the increase in the developed shear stress within the substrata. If the developed shear stress is greater than the shear strength of soil, the liquefaction or cyclic mobility might occur within the substrata depending on the type of soil.

### 4.2 *Influence of PGA of different input motions on the GRA of Itanagar city*

Figures 20(a-d) present the variations of acceleration, amplification factor (indication of amplification or deamplification of seismic wave), strain and shear stress ratio along with depth using the acceleration-time history of Coyote EQ ($M_w$5.7, PGA=0.12g), Kocaeli EQ ($M_w$7.4, PGA=0.22g), Loma Gilroy-2 EQ ($M_w$6.9, PGA=0.36g), Mammoth Lake EQ ($M_w$4.9, PGA=0.43g) and Kobe EQ ($M_w$6.9, PGA=0.82g) motions. Figure 20a presents the variation of acceleration with depth, which indicates that the input motion of different seismic energy will have a different impact on GRA. Based on bedrock PGA ranging from 0.12g to 0.82g, the surface level PGA is found to be in the range of 0.26g to 1.03g. The input motion with less seismic energy (PGA=0.12g) amplify more in comparison to the high seismic energy (PGA=0.82g), as shown in Fig.20b. However, the amplification of Loma Gilroy-2 motion at surface level is found to be comparatively notably higher than the other input motion. Further, the amplification factor is found to be in the range of 1.13 to 2.88, for a frequency range of 1 Hz to 5 Hz, corresponding to the bedrock

PGA ranging between 012g - 0.82g. Similar results of amplification factor ranging from 2.1-4.3, for Guwahati city, have been reported by Kumar et al. [60] using input motion PGA ranging from 0.102g-0.34g. Raghukanth et al. [61] have also reported the amplification factor of seismic wave ranging from 1.0 - 2.5 at the surface level for the earthquake motion of PGA 0.14g - 0.19g. Figure 20c presents the variations of shear strain at CM residence site using input motion of Coyote EQ, Kocaeli EQ, LG-2 EQ, Mammoth Lake EQ and Kobe EQ, wherein it can be noticed that the maximum strain near the surface level is 0.028%, 0.048%, 0.276%, 0.168% and 0.319%, respectively. Figure 20d presents the variation of shear stress ratio with depth and it can be seen that the maximum shear stress ratio is 0.192, 0.286, 0.849, 0.648 and 0.914 corresponding to the Coyote EQ, Kocaeli EQ, LG-2 EQ, Mammoth Lake EQ and Kobe EQ, respectively.

**Table 2** Summary of the results of surface level PGA and the amplification factor

| **Input Motion** | **PGA (g) at Surface level** | | | | | | | **Amplification Factor (AF)** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **BH-1** | **BH-2** | **BH-3** | **BH-4** | **BH-5** | **BH-6** | **BH-7** | **BH-1** | **BH-2** | **BH-3** | **BH-4** | **BH-5** | **BH-6** | **BH-7** |
| **Coyote (1979) (0.12g)** | 0.262 | 0.299 | 0.234 | 0.218 | 0.283 | 0.326 | 0.248 | 2.181 | 2.490 | 1.947 | 1.818 | 2.358 | 2.719 | 2.069 |
| **Kocaeli (1999) (0.22g)** | 0.313 | 0.547 | 0.360 | 0.259 | 0.679 | 0.312 | 0.720 | 1.422 | 2.486 | 1.637 | 1.178 | 3.089 | 1.418 | 3.271 |
| **Loma Gilroy-2 (1989) (0.36g)** | 1.039 | 1.279 | 0.934 | 0.820 | 1.518 | 1.153 | 1.568 | 2.880 | 3.552 | 2.594 | 2.278 | 4.217 | 3.203 | 4.356 |
| **Mammoth Lake (1980) (0.43g)** | 0.723 | 0.780 | 1.043 | 0.852 | 0.977 | 0.803 | 1.041 | 1.681 | 1.814 | 2.426 | 1.980 | 2.272 | 1.868 | 2.420 |
| **Kobe (1995) (0.82g)** | 0.932 | 1.041 | 0.862 | 0.840 | 1.853 | 0.880 | 1.189 | 1.137 | 1.269 | 1.051 | 1.025 | 2.260 | 1.073 | 1.449 |

**Note:** BH-1 (CM Residence), BH-2 (Itafort), BH-3 (MOWB-II), BH-4 (Rajbhawan), BH-5 (Secretariat), BH-6 (State Assembly), BH-7 (VIP Housing)

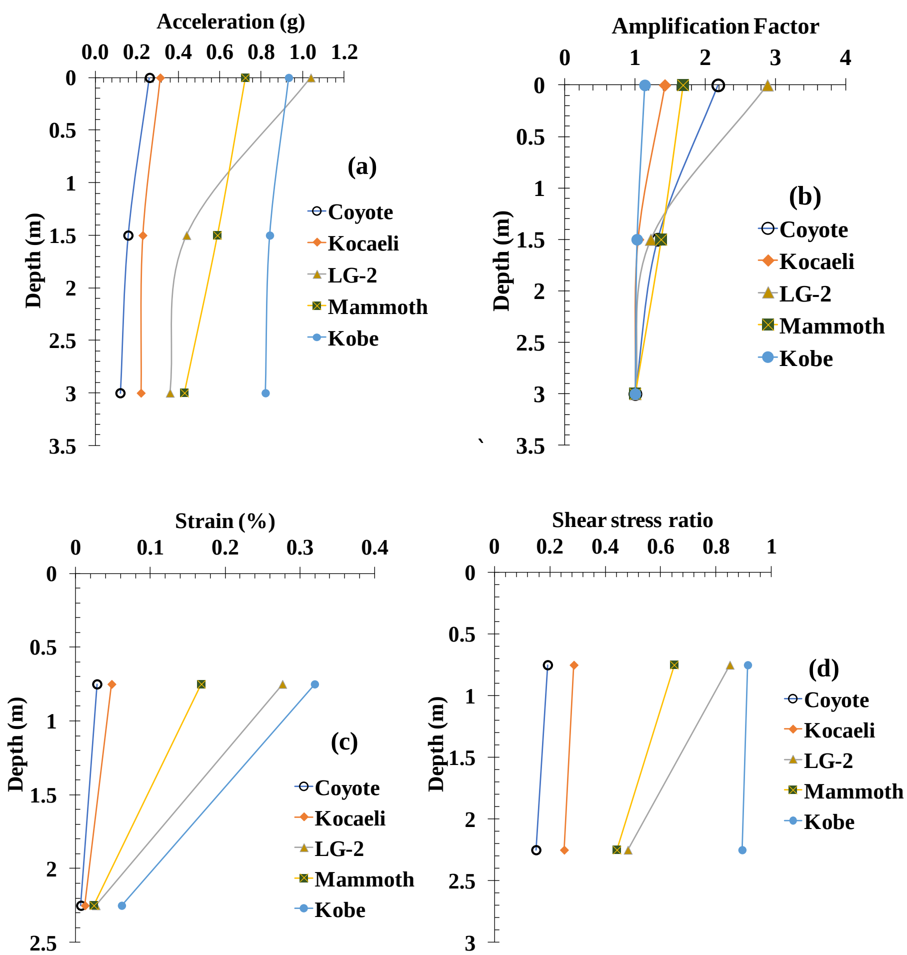


**Fig. 20** Variation of (a) peak horizontal acceleration (b) amplification factor (c) peak shear strain (d) shear stress ratio for varying seismic energy imparted by strong motions having various PGA and subjected upon the 3 m deep borehole at CM residence site.

Similar GRA study has been conducted for the Secretariat borehole site, which has larger borehole depth in comparison to CM residence, wherein the results are presented in Fig. 21. Figure 21a presents the variations of ground acceleration with depth at Secretariat site using all five input motions. It demonstrates that the acceleration at surface level is in the range of 0.24g to 1.8g for the input bedrock motion ranging from 0.12g to 0.82g and the maximum acceleration is found to be higher for Kobe motion. Figure 21b presents the acceleration amplification factor with depth and it exhibits that the range of amplification factor is 2.36 to 4.22. Further, Nath et al. [62] have reported similar observations for amplification factor for the Guwahati city. Moreover, based on the comparison of the results of GRA presented in Fig. 20b and Fig. 21b, it can be stated that the variation of acceleration or amplification factor depends on the characteristics of soil as well as strong motion parameters. Figure 21c and Fig. 21d presents the variations of strain and stress ratio with depth, respectively, at the secretariat site using five chosen earthquake motions. The maximum value of strains was observed in the range of 0.039% - 1.33% near the surface. It can also be noticed that the site subjected to Kobe motion exhibits higher strain ranges. The stress ratio ranging from 0.28 to 1.45 is observed near the surface level. The development of high value of shear stress ratio ( > 1) might be an indication of development of high amount of stress within the ground which may cause the catastrophic damage.

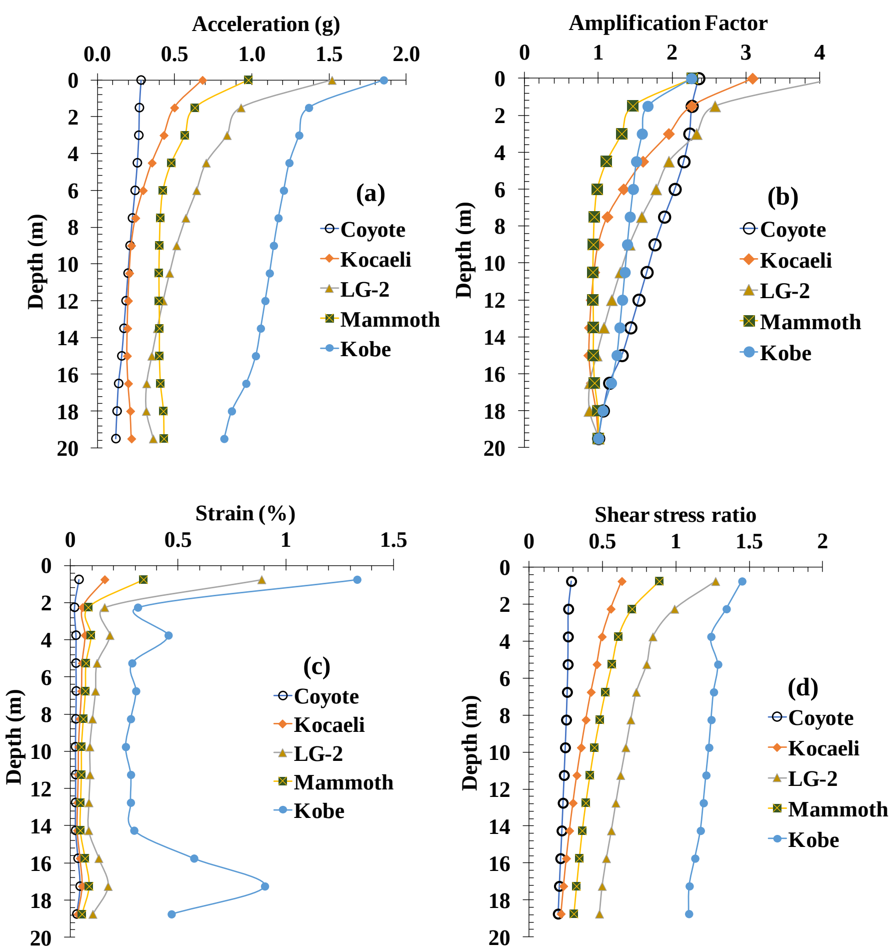


**Fig. 21** Variation of (a) peak horizontal acceleration (b) amplification factor (c) peak shear strain (d) shear stress ratio for varying seismic energy imparted by strong motions having various PGA and subjected upon the 19.5 m deep borehole at Secretariat site

### 4.3 *Influence of soil variability on spectral acceleration*

In GRA, the Spectral Acceleration (SA) indicates the maximum response of soil mass under free-field conditions, which is extremely important for the development of design spectral acceleration. The free-field design response spectrum can be utilized to design seismically resilient structure since, it accounts the effect of site geology and soil properties. The design spectral acceleration (for 5% of critical damping) is an average smoothened graph, which demonstrates the maximum acceleration for the expected earthquake at the base of single degree of freedom system as a function of natural frequency or natural period of oscillation [4]. This graph allows the engineers to choose a design value of acceleration according to the input bedrock PGA, soil conditions and time period. Further, the modification in the spectral acceleration as well as in the structural design can also be done with the aid of this graph to increase the safety of buildings during earthquakes in case the expected earthquake accelerations are higher than the design value. For Secretariat site, Fig. 22 presents the response spectrum (for 5% damping ratio) at the surface level using input ground motions of PGA = 0.12g, 0.22g, 0.36g, 0.43g and 0.82g. The design acceleration response spectrum proposed by IS1893-2016 [16] for hard, medium and soft soils are also plotted along with. It can be seen from Fig. 22 that the maximum spectral acceleration at the Secretariat site based on Kobe motion corresponds to a period of 0.34s and is found significantly higher (i.e., $SA_{max}$ = 9.15g) as compared to that obtained from other motions. This is mainly attributed to the fact that that one of the natural frequencies of Kobe motion (frequency of the second mode, $f_2$) is approximately 3Hz (see Fig. 6e), which is close to the fundamental frequency of secretariat site i.e. $f$ = 3.49 Hz (based on $f = (V_s/4H)$ according to [4]). The nearness of these frequencies has possibly led to the high magnitude of the spectral acceleration. It is worth mentioning that Kobe motion has a noticeably high PGA and Arias intensity in comparison to the other motions considered in the study and, consequently, can produce high magnitudes of spectral acceleration in the vicinity of its natural frequencies. The maximum spectral acceleration ($SA_{max}$) at the Secretariat site is found to be 1.01g, 2.47g, 4.78g and 3.32g at period 0.31s, 0.17s, 0.28s and 0.23s corresponding to the Coyote EQ, Kocaeli EQ, LG-2 EQ and Mammoth Lake EQ, respectively.

Figure 23 presents the spectral acceleration near surface level at all seven sites considering 5% damping ratio and Coyote EQ motion (PGA=0.12g) to observe the impact of soil variability on the design response spectrum. It can be seen from Fig. 23 that $SA_{max}$ is 0.874g, 0839g, 0.725g, 0.873g, 1.015g, 1.182g and 1.135g corresponding to the period of 0.094s, 0.12s, 0.04s, 0.047s, 0.305s, 0.039 and 0.127s, respectively, at CM residence, Itafort, MOWB-II, Raj

Bhawan, Secretariat, State Assembly and VIP Housing locations, respectively. The value of $SA_{max}$ at surface level, using Coyote EQ motion of PGA=0.12g, is found to be lesser than the spectral acceleration of hard, medium and soft soil reported by IS1893-2016 [16]. Thus, it can be stated that since the observed $SA_{max}$ from GRA is lesser than the $SA_{max}$ reported by IS1893-2016 [16], the structural design might be in the safer side. However, the impact of high bedrock PGA (see Fig. 25) is found to be significantly different than the low bedrock PGA (see Fig. 23).

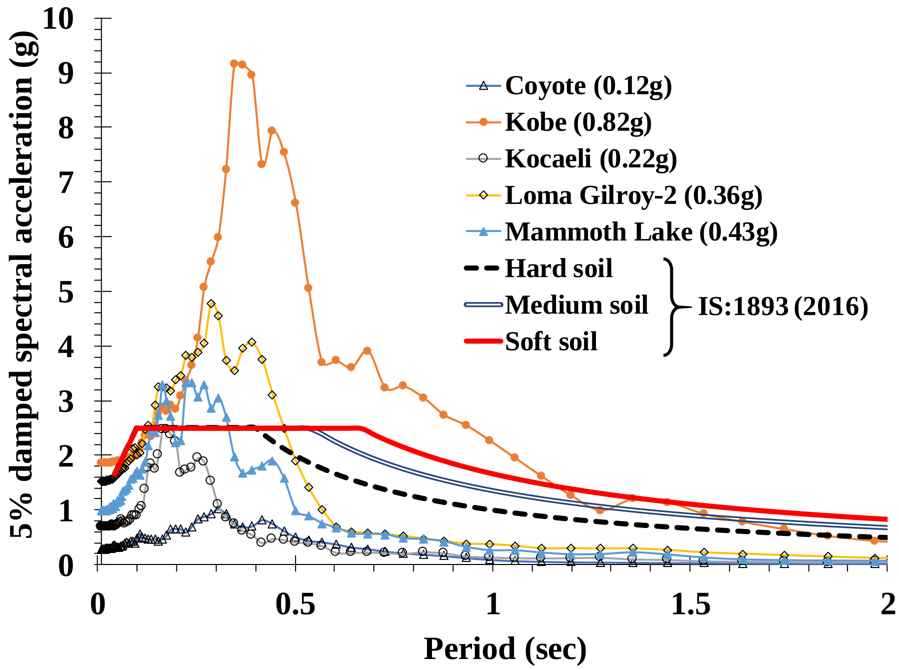


**Fig. 22** Free field response spectrum at the surface of Secretariat site from EQL analysis, considering 5% damping ratio and using different input motions along with design response spectrum proposed by IS1893-2016 [16] for hard, medium and soft soil types

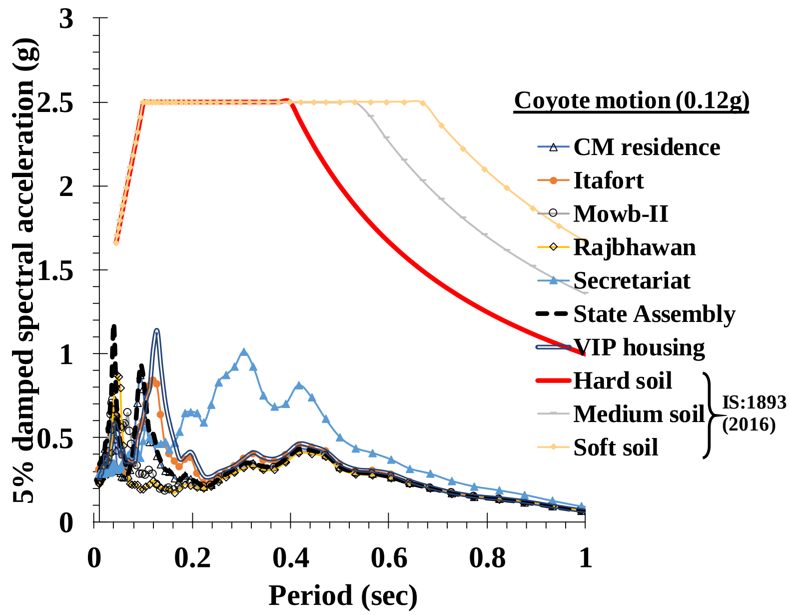


**Fig. 23** Free field response spectrum at the surface of different sites from EQL analysis considering 5% damping ratio and using 1979 Coyote EQ motion (0.12g) as well as design response spectrum proposed by IS1893-2016 [16] for hard, medium and soft soil types

In order to exhibit the impact of soil variability on the design response spectrum Figure 24 presents the spectral acceleration near surface level at the seven sites considering 5% damping ratio and Loma Gilroy-2 EQ motion (PGA=0.36g). It can be seen that $SA_{max}$ is 3.53g, 4.69g, 3.9g, 3.32g, 4.78g, 3.88g and 6.28g corresponding to the period of 0.12s, 0.15s, 0.082s, 0.06s, 0.286s, 0.12s and 0.154, respectively, at CM residence, Itafort, MOWB-II, Raj Bhawan, Secretariat, State Assembly and VIP Housing location, respectively. Figure 25 presents the spectral acceleration near surface level at seven soil sites considering 5% damping ratio and Kobe EQ motion (PGA=0.82g) to observe the impact of soil variability on the design response spectrum. It can be seen that $SA_{max}$ is 3.15g, 3.54g, 2.83g, 2.73g, 3.1g, 9.15g and 3.63g corresponding to the period 0.35s, respectively, at CM residence, Itafort, MOWB-II, Raj Bhawan, State Assembly, Secretariat and VIP Housing location, respectively. It can also be seen that the value of $SA_{max}$ at surface level using Kobe EQ motion of PGA=0.82g is higher than the spectral acceleration of hard, medium and soft soil reported by IS1893-2016 [16]. Thus, it can be stated that the observed $SA_{max}$ from GRA using high intensity Kobe motion is more vulnerable to the structures.

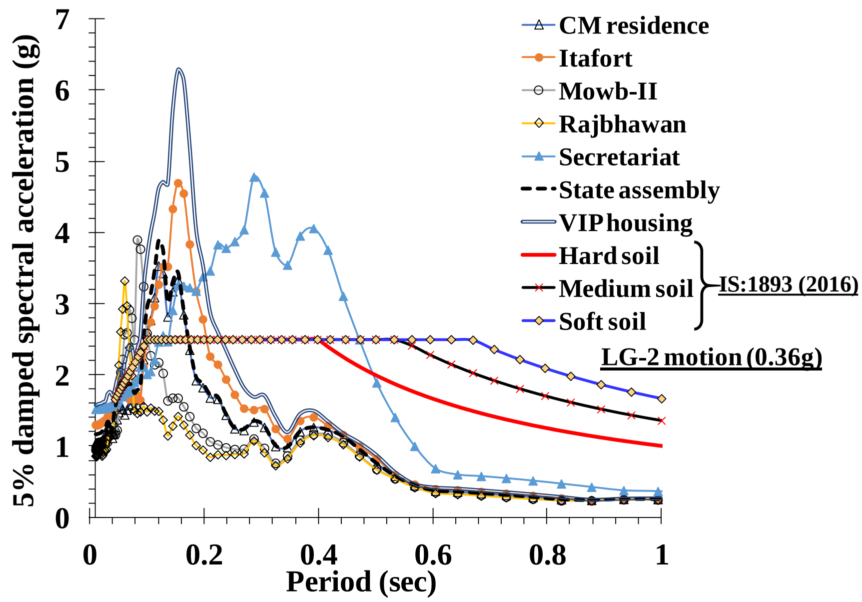


**Fig. 24** Free field response spectrum at the surface of different sites from EQL analysis considering 5% damping ratio and using 1989 Loma Gilroy-2 EQ motion (0.36g) as well as design response spectrum proposed by IS1893-2016 [16] for hard, medium and soft soil types

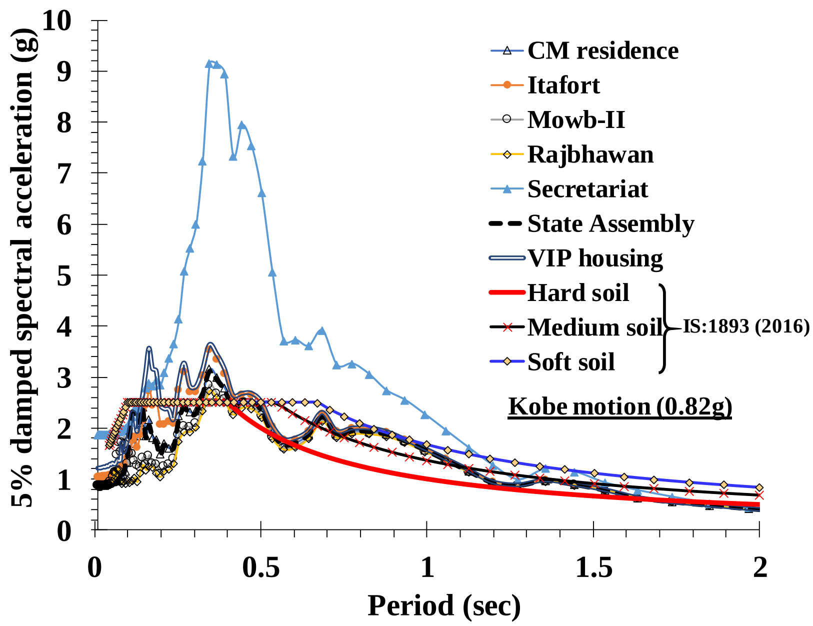


**Fig. 25** Free field response spectrum at the surface of different sites from EQL analysis considering 5% damping ratio and using 1995 Kobe EQ motion (0.82g) as well as design response spectrum proposed by IS1893-2016 [16] for hard, medium and soft soil types

In comparison to the other soil sites, the higher value of spectral acceleration at Secretariat site is attributed to the presence of the silt or clayey soil. Moreover, the summary of maximum spectral acceleration and the corresponding time period(s) for all seven boreholes using input motion of Coyote EQ (0.12g), Kocaeli EQ (0.22g), LG-2 EQ (0.36g), Mammoth Lake EQ (0.43g) and Kobe EQ (0.82g) are presented in Table 2. From Table 2, it can also be concluded that $\gamma_{max}$ at surface level depends on the input motion as well as local soil site characteristics. However, the effect of frequency content parameters such as earthquake frequency, predominant period, arias intensity, bracketed duration and other earthquake-associated parameters on the spectral acceleration are beyond the scope of present study. Figures 26, 27 and 28 show the contour map of maximum spectral acceleration at surface level for different sites using Coyote EQ motion Loma Gilroy-2 EQ motion and Kobe EQ motion, respectively. It can be seen that Secretariat have site has the highest spectral acceleration when subjected to three the input motions.

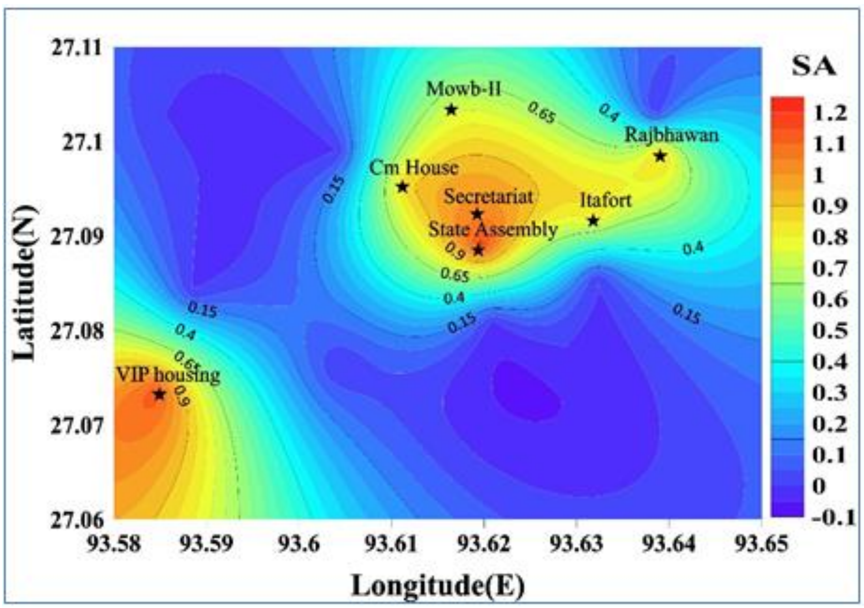


**Fig. 26** Contour map of maximum spectral acceleration in Itanagar region subjected to bedrock PGA =0.12g of Coyote motion

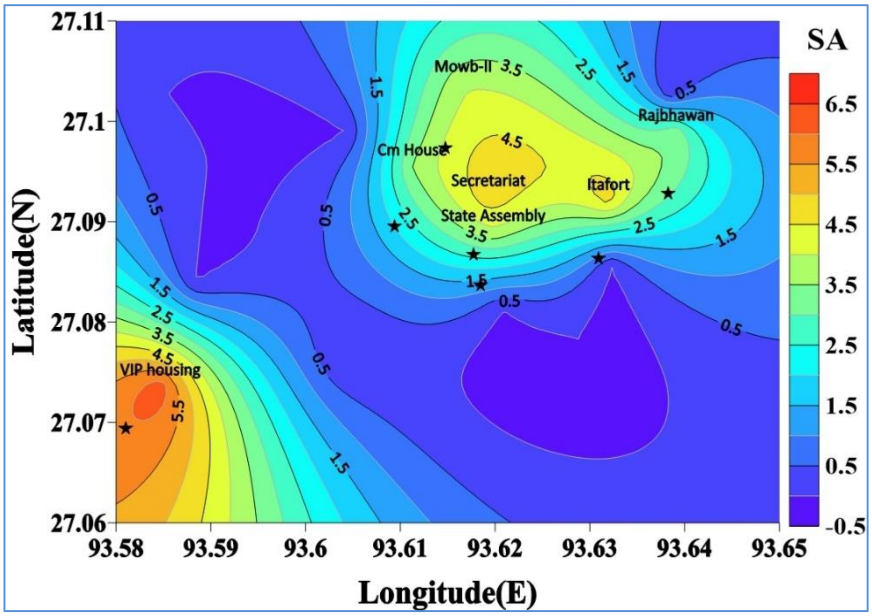


**Fig. 27** Contour map of maximum spectral acceleration in Itanagar region subjected to bedrock PGA =0.36g of Loma Gilroy-2 motion

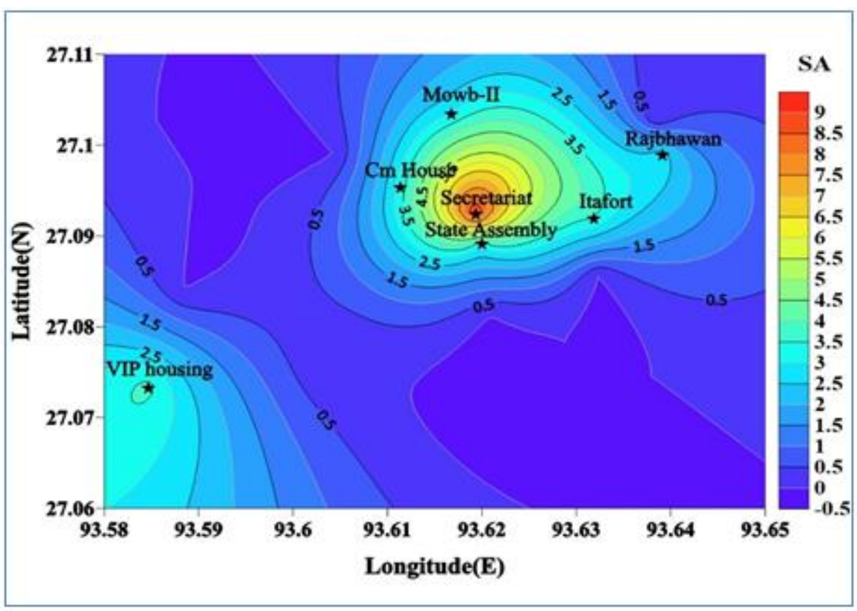


**Fig. 28** Contour map of maximum spectral acceleration in Itanagar region subjected to bedrock PGA =0.12g of Kobe motion

**Table 3** Summary of the results of maximum spectral acceleration at seven boreholes

| Input Motion | Maximum Spectral Acceleration ($SA_{max}$) (g) & Corresponding period (s) | | | | | | |
|---|---|---|---|---|---|---|---|
| | **BH-1** | **BH-2** | **BH-3** | **BH-4** | **BH-5** | **BH-6** | **BH-7** |
| **Coyote (1979) (0.12g)** | 0.873 (0.094) | 0.839 (0.120) | 0.724 (0.039) | 0.872 (0.047) | 1.014 (0.305) | 1.181 (0.039) | 1.135 (0.128) |
| **Kocaeli (1999) (0.22g)** | 1.199 (0.164) | 3.188 (0.136) | 2.306 (0.068) | 0.968 (0.054) | 2.476 (0.174) | 1.211 (0.164) | 3.787 (0.154) |
| **Loma Gilroy-2 (1989) (0.36g)** | 3.533 (0.120) | 4.698 (0.154) | 3.9 (0.083) | 3.324 (0.061) | 4.784 (0.287) | 3.883 (0.120) | 6.286 (0.154) |
| **Mammoth Lake (1980) (0.43g)** | 2.355 (0.136) | 3.945 (0.164) | 3.023 (0.078) | 3.487 (0.057) | 3.329 (0.238) | 2.424 (0.136) | 5.425 (0.164) |
| **Kobe (1995) (0.82g)** | 3.155 (0.345) | 3.541 (0.345) | 2.836 (0.345) | 2.736 (0.345) | 9.152 (0.345) | 3.1 (0.345) | 3.628 (0.345) |

**Note:** BH-1 (CM Residence), BH-2 (Itafort), BH-3 (MOWB-II), BH-4 (Rajbhawan), BH-5 (Secretariat), BH-6 (State Assembly), BH-7 (VIP Housing)

## 7. Conclusions

Equivalent Linear (EQL) Ground response analyses have been carried out for Itanagar region subjected to five different earthquake motions. For the analysis, based on the prevalent seismicity of Itanagar (Arunachal Pradesh) and the region being located in Zone-V as per IS1893-2016 [16], five input strong motion of PBRA = 0.12g, 0.22g, 0.36g, 0.43g and 0.82g have been chosen. As a result of the seismic GRA analysis, the following conclusions have been drawn concerning variations in acceleration, amplification and deamplification of seismic waves, shear strain, shear stress ratio, and horizontal displacement with depth.

- The PGA at surface level was found to be in the range of 0.218g - 0.326g, 0.259g - 0.720g, 0.820g - 1.568g, 0.723g - 1.043g and 0.840g - 1. 853g, using input motion having bedrock PGA of 0.12g, 0.22g, 0.36g, 0.43g and 0.82g, respectively. This indicates the amplification or de-amplification of seismic waves. The seismic waves amplified by 335% over the surficial levels, whereas deamplification in the tune of 13% is noted at a depth of nearly 13 m -14 m. The amplification factor is found to be in the range of 1.05 - 4.36 for the given input acceleration ranging from 0.12 g- 0.82 g. As a consequence, it can be conceded that seismic GRA in Itanagar region is highly influenced by input motion, local geology and soil characteristics.
- The maximum shear strains were found to be 0.5%, 0.7%, 0.28%, 0.17% and 1.32% for the input motion having PBRA = 0.12g, 0.22g, 0.36, 0.43g and 0.82g, respectively. Hence, it is conceded that soils in the Itanagar region experience higher shear strain when subjected to higher input PGA, and is influenced by local soil conditions as well as characteristics of the ground motion.
- Shear stress ratio was found to be in the range of 0.19 - 0.28, 0.25 - 0.67, 0.77 - 1.43, 0.64 - 0.98 and 0.86 - 1.45 for input motion of PBRA = 0.12g, 0.22g, 0.36g, 0.43g and 0.82g, respectively. It can be concluded that the shear stress ratio significantly depends on the energy associated with input motion as well as local soil conditions. Thus, it can be stated that the higher ground motion intensity in the Itanagar region would cause greater shear stress, which might lead to the potential damage of structures above and below the ground.
- The maximum spectral acceleration ($SA_{max}$) for Itanagar region was found to be in the range of 0.724g - 9.152g, for the given input motion PBRA range i.e., from 0.12 g - 0.82 g. The results of $SA_{max}$ at surface level are associated with local soil conditions and their dynamic properties, which indicates the significance of free field seismic GRA. Moreover, the results of $SA_{max}$ obtained in the Itanagar region can be further utilized for the seismic risk assessment in the region as well as for urban planning.

According to the findings of this study, the obtained response parameters will help determine the height, lateral dimensions and natural period of new structures to be constructed at Itanagar, as well as provide guidelines for assessing seismic response to new structures. It would be possible to assess the structural vulnerability to different ground shakings with such knowledge. Based on the current finding, seismic requalification works can be carried out in order to minimize their seismic vulnerability and decisions about retrofitting the existing structures can be taken based on their current health. In areas with high ground accelerations, foundations and structures must be designed with special care. The current understanding in regard to the ground response analysis study for the Itanagar region reported herein can be further improved with the regional assessment of the dynamic soil properties from field and laboratory investigations, identification of the subsurface shear wave velocity profile from geophysical investigations, and investigating the influence of other strong motion characteristics related to the frequency and duration of the motion on the responses from ground response analysis.

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**Compliance with Ethical Standards**

**Conflict of Interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Ethical Approval:** This article does not contain any studies with human participants or animals performed by any of the authors.

**Informed Consent:** For this type of study, formal consent is not required.

**Author Contributions:** AKA: Conceptualization, Formal analysis, Writing – Original preparation; AD & SK: Revision and Editing of drafted manuscript; JT: Supervision, Formal analysis, Revision and editing of drafted manuscript.

**Data Availability Statement**

Data sets generated during the current study are available from the corresponding author on reasonable request.

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