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Estimation of Ground Motion Amplification for Sub-Himalayan Strata due to Hypothetical Earthquake Motions

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Abstract

Himachal Pradesh state is located in seismically active western Himalayas (India) and its seven districts are in seismic zone V and other in zone IV as per the seismic code of India. Ninety% area of Hamirpur district, the studied area, lies in zone V. Peak ground acceleration (PGA) is one of the most important seismic response parameters in structural seismic design, largely influenced by the sub-soil and input seismic motion characteristics. In the present work, the primary objective is to identify the areas in the district that are prone to amplification of peak ground acceleration and can be delineated for infrastructural planning. Peak ground acceleration is one of the most important parameters used in seismic design of the structures. It is estimated using the computer programme ProShake, wherein the soil parameters from 181 borehole profiles up to 30 m depth and software in-built standard earthquake input motions of magnitude 6.9, 7.0, and 7.2 used as the input parameters. The output peak ground acceleration range from 0.24 g to 0.72 g at the ground surface and from 0.21 g to 0.54 g at a depth of 10 m. There is an attenuation of peak ground acceleration at 30 m depth. The estimation of peak ground acceleration will play an important role in delineating the starta having higher peak ground acceleration amplification. This information can be effectively used for planning of important infrastructure projects like hospitals, educational institutions, and commercial establishments in an economical way in the studied area.

1. Introduction

The state of Himachal Pradesh is situated at 33° 18' 00"-36° 00' 00" North (latitude) and 75° 36' 00" East (longitude) in the western Himalayas. The terrain of the state is hilly ranging from Shiwaliks in the south to tall snowclad Pirpanjals in the north. This area contains the Himalayan frontal thrust, main boundary thrust, Krol, Giri, Jutogh, and Nahan thrusts. There are several smaller faults such as the Kaurik fault, which caused the earthquake in 1975. The state has experienced more than 250 earthquakes of magnitude more than 4.0 and 62 earthquakes of magnitude more than 5.0 on the Richter scale. Kangra earthquake of 4 April 1905 was the biggest one with moment magnitude 7.8 (M_w). The Himalayan orogeny is responsible for the earthquake activity in Himachal Pradesh. The state is the most at risk from the hazard of earthquakes due to its strategic location along the main Himalayan thrust. The rocky strata in the lower Himalayas are fragmented, and there is little soil cover. After every 5-7 kilometres, there is a considerable change in the soil/rock strata. The huge variations in the sub-soil profile in Himachal Pradesh have a substantial impact on the seismic response of the strata [1-2]. However, it is important to note that areas close to faults do not necessarily pose a greater risk than those farther away because earthquake damage depends on a variety of factors including sub-surface geology, earthquake magnitude and its location, the quality of the building stock, and structural features. Seven districts in Himachal Pradesh are under seismic zone V [3], and are at risk of strong earthquakes of intensity IX or greater: Kangra (98.60%), Mandi (97.40%), Hamirpur (90.90%), Chamba (53.20%), Kullu (53.10%), Una (37.00%), and Bilaspur

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(25.30%) (www.hpsdma.nic.in). The remaining districts of Lahul and Spiti, Kinnaur, Shimla, Solan, and Sirmaur are under seismic zone IV and susceptible to moderate earthquakes with an intensity of VIII or less. The present work is focused on district Hamirpur that is having five administrative sub-divisions: Hamirpur, Barsar, Nadaun, Sujanpur, and Bhoranj.

In addition to the structural features, earthquake source characteristics and local site conditions significantly influence how a structure behaves during an earthquake. The characteristics of earthquake waves change during their propagation through soil layers because of varying soil characteristics and the response of soil strata changes due to the induced excitations. When the seismic wave travels from high-density soil layer to low-density soil layer, its velocity decreases but its amplitude increases [4-6], as such the low-density layer cannot be detected by experimental seismic methods and can be termed as a blind layer. The main characteristics of strong ground motion, *i.e.* amplitude, frequency content, and duration are strongly influenced by the local site conditions. The extent of their influence to largely depends upon the material properties of the subsurface strata. Therefore, identification of soft soil deposits prone to ground motion amplification plays an important role in seismic microzonation. The damage pattern observed during several past earthquakes like Mexico earthquakes (1985), San Francisco earthquake (1989), Los Angeles earthquake (1995), and Bhuj earthquake (2001) have shown that soft soils play an important role in ground motion amplification [7-11]. The main cause of the frequent occurrence of amplification phenomena on soft deposits is the trapping of seismological waves within the soft deposits [12-15]. Due to this behaviour, seismic waves travel through tens of kilometres of rock and often less than hundred meter of soil [16]. Trivedi [17] estimated the soil amplification of PGA of Ahmedabad region ranging from 0.098 g to 0.198 g. Shiuly *et al.* [18] studied the effect of soil on ground motion amplification of soft sedimentary deposits in Kolkata city and revealed that unexpected damage may occur even during moderate earthquake due to double resonance effect of high-rise buildings with 5-7 storeys. Kumar *et al.* [19] conducted seismic classification for Amaravati city (India) and observed that city falls under class D as per the National Earthquake Hazard Reduction Programme (NEHRP) provisions. Boruah *et al.* [20] in their study estimated site-specific amplification factors at Shillong city in the maximum range of 2.77 - 2.92 and in minimum range of 2.01 - 2.16 with PGA values at surface ranging from 0.6 g to 0.94 g under probable earthquake of magnitude 8.1. Jena *et al.* [21] estimated PGA in Odisha (India) and prepared PGA maps showing variation of PGA from 0.0017-0.12 g under earthquake of 5 M_w. They classified the state into four sections based upon the PGA range: 0.0017 -0.014 g, 0.014 -0.039 g, 0.039- -0.092 g, and 0.092-0.18 g. Vallianatos *et al*. [22] developed earthquake early warning system (EEWS) for quick-acting seismic risk mitigation taking PGA as one of the seismic response parameters. For probabilistic seismic hazard assessment of Uttarakhand (India), Gupta *et al.* [23] presented spatial distribution of arias intensity and PGA values in seismic hazard maps. At the surface-level a variation of PGA from 0.21- -0.72 g and 0.30 g to 1.09 g for 10% and 2% exceedance probability in 50 years was suggested.

In the present study, PGA amplifications due to soil above engineering bed rock have been estimated for 181 borehole locations spread across the Hamirpur district using one dimensional seismic wave propagation computer programme ProShake. The main objective of the present study was to identify the areas in Hamirpur district that are prone to ground motion amplifications and mapping the studied area with PGA values. This study will help in identifying the starta having higher PGA amplifications and delineating them from the remaining area for planning, designing and construction of important structures.

2. Geotechnical Data

Hamirpur district is situated between the latitude of 31° 25′ 00″ to 31° 52′ 00″ North and the longitude of 76° 18′ 00″ to 76° 44′ 00″ East, and lies in seismic zone V. The terrain in the district ranges from 400 to 1100 metres above mean sea level. It has an area of 1118 square kilometres covering five administrative sub-divisions and a population density of 407 people per square kilometre. The sub-soil profile was data collected from more than 181 boreholes, shown in Figure 1, spread over the entire region of the district. Hamirpur sub-division contains 23 boreholes whereas Nadaun, Sujanpur, Bhoranj, and Barsar sub-divisions contain 34, 29, 42, and 53 boreholes, respectively.

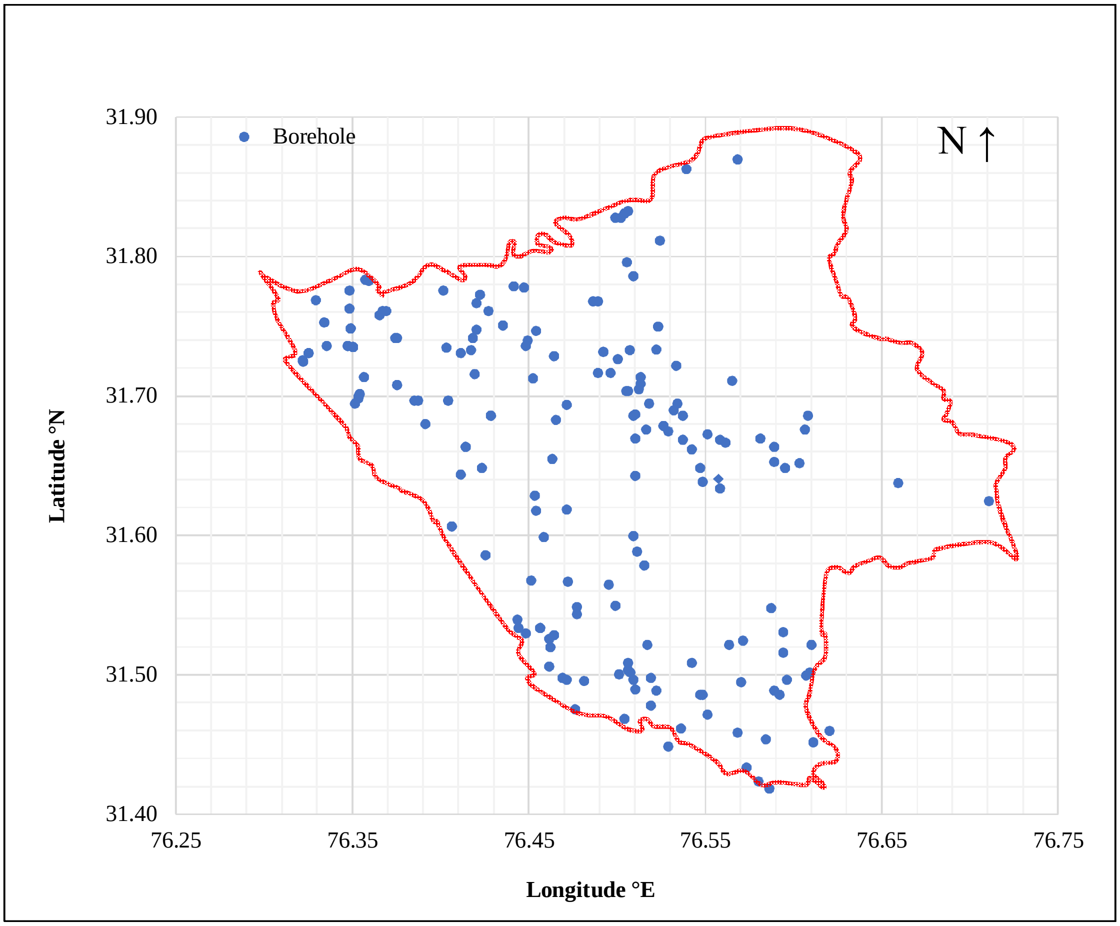


Figure 1. Location of boreholes in studied area.

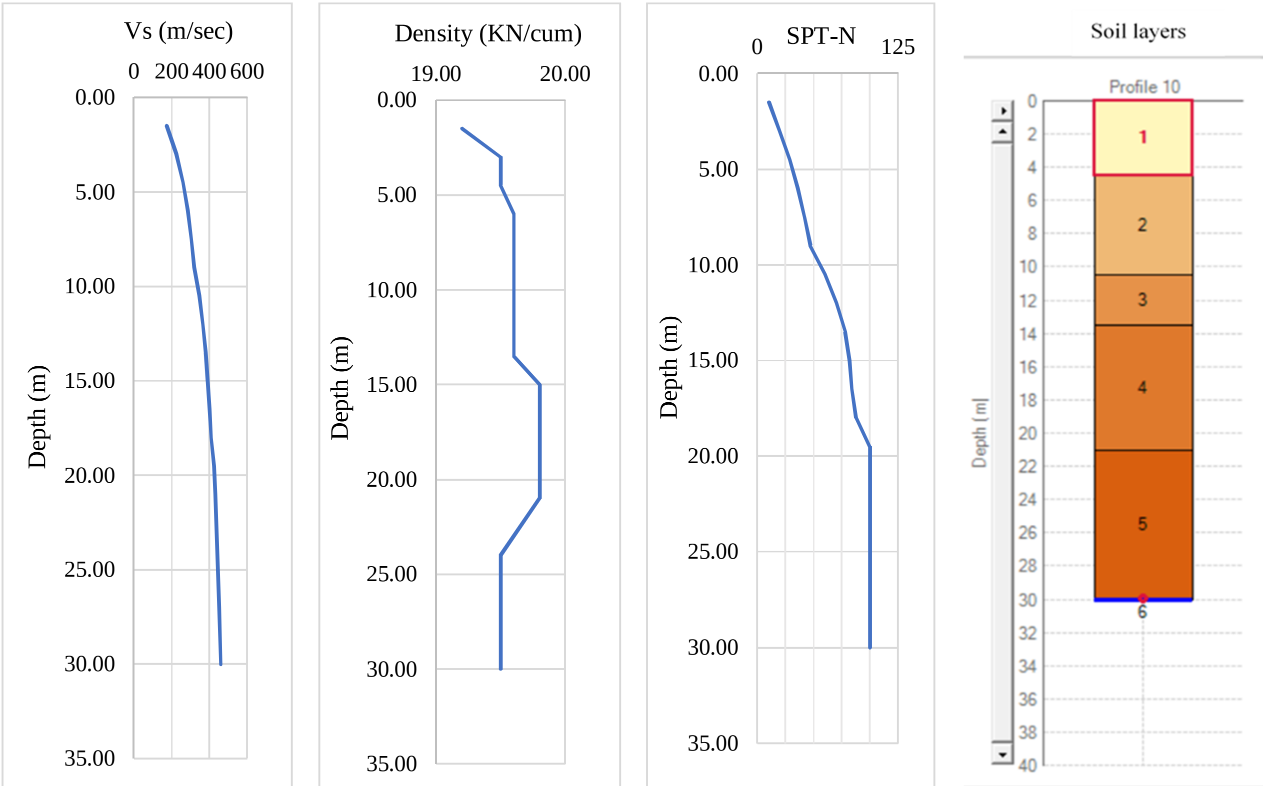
Standard penetration tests were performed in boreholes up to 30 m depth to determine the SPT-N values. In-situ densities of soil layers encountered in the boreholes were determined in the laboratory from the field soil samples. Clay with unconsolidated boulders, clay with pebbles, clay, boulder conglomerate, clay with sandy matrix, clay mixed with pebbles, gravel and boulders, sand stone, clay with boulders, clay stone with boulders, boulders mixed with clay, boulders with sand, boulders, saturated silt, medium-grained saturated sandy silt, and conglomerate with sandy matrix were the soil types observed in the studied area. The density of the soil layers across all sub-divisions is variable with depth, and it ranges from 17.30 kN/m^3 to 21.20 kN/m^3. Typical soil profile of borehole No. 34 of Nadaun sub division is shown in Table 1 along with soil properties at different depths. It has five soil layers and sixth one corresponds to the hypothetical bedrock level. The corrected SPT-N values have been used for estimation of shear wave velocity using formula $V_s = 105.8\ N^{0.187}\ D^{0.179}$ applicable for all type of soils [24] and the values for a typical borehole are presented in Table 1. The sub-soil profiles are observed up to 30 m depth and hypothetical hard strata (the engineering bedrock) was considered at 30 m depth in the study for estimation of ground seismic response.

Table 1. Typical bore-log profile.

Borehole No. and location	**Depth (m)**	**Soil strata**	**SPT-N value**	**Water table depth (m)**	**Density (kN/m³)**	**Shear wave velocity (m/s) $V_s = 105.8\ N^{0.187}\ D^{0.179}$** Tamura and Yamazaki [24]
34		**Nadaun subdivision** (31° 44' 07" N 76° 21' 00" E)				
		Sand mixed boulders of sand stone and quartzite, cobbles with clay:				
Layer 1	1.5	Soft	10	**30.00**	19.2	174.99
	3.0	Medium	20		19.5	225.52
	4.5	Medium	29		19.5	259.94
		Average value	**19.67**		**19.4**	**220.15**
Layer 2	6.0	Medium to Hard	36		19.6	284.97
	7.5	Medium to Hard	42		19.6	305.26
	9.0	Medium to Hard	47		19.6	322.09
	10.5	Medium to Hard	60		19.6	346.57
		Average value	**46.25**		**19.6**	**314.72**
		Sand stone:				
Layer 3	12.0	Hard	70		19.6	365.34
	13.5	Hard	78		19.6	380.75
		Average value	**74**		**19.6**	**373.04**
Layer 4	15.0	Very hard	82		19.8	391.64
	16.5	Very hard	84		19.8	400.18
	18.0	Very hard	88		19.8	410.01
	19.5	Very hard	100		19.8	425.99
	21.0	Very hard	100		19.8	431.68
		Average value	**90.8**		**19.8**	**411.90**
		Sand stone, pebbles:				
Layer 5	24.0	Very hard	100		19.5	442.12
	27.0	Very hard	100		19.5	451.54
	30.0	Very hard	100		19.5	460.14
		Average value	**100**		**19.5**	**451.27**

2.1 ProShake software

ProShake software [25] was used to calculate one-dimensional seismic ground response of horizontally layered soil deposits in the studied area. It is a one dimensional, equivalent linear ground computer programme for response analysis developed by EduPro Civil Systems, Inc., Washington (U.S.A). It is an effective and simple software program having many features for data entry, analysis, viewing, and documenting results in a more efficient and effective manner. It has built-in modulus reduction & damping models, graphical displays of soil profile and input motion parameters, graphical displays of a wide range of output parameters, and animation of ground response. It is organized into three main modules namely Input Manager, Solution Manager and Output Manager. The input manager arranges the input data into projects, which include numerous soil profiles and each project contains soil profile and ground motion data. Site response analyses are run in the solution manager; while the output manager presents data in a variety of helpful charts and export it to a variety of spreadsheet formats for use in other graphical programs or long-term storage. ProShake computes value of PGA at the center of each soil column in a borehole. The ProShake software has approximated the non-linear hysteretic stress-strain behavior of the soil by comparable linear soil parameters. Typical variation of input parameters used for analysis in ProShake software shown in Figure 2.



(a) (b) (c) (d)

Figure 2. Typical variation of input parameters in borehole 34 of Nadaun sub-division (a) shear wave velocity (b) density (c) SPT-N values (d) soil layers and water table level.

2.2 Earthquake input motions

For evaluation of ground motion amplification, appropriate natural acceleration time histories or synthetic acceleration time histories are required. For the present study, standard input acceleration–time histories in vertical directions of three earthquakes motions were considered and their characteristics are reproduced in Table 2. As the studied area previously experienced an average seismic motion of magnitude 7.0, three earthquakes were taken into consideration for the site response studies with magnitudes ranging from 6.9 to 7.2. Acceleration time histories of the considered earthquake motions are shown in Figs. 3, 4, and 5.

Table 2. Input motion parameters of the synthetic earthquakes [25].

Earthquake motion	Peak velocity (m/s)	Peak acceleration (g)	Peak displacement (m)	Response spectrum intensity (g^2)	Predominant period (s)	Spectral acceleration @ 1.0 s (g)	RMS acceleration (g)
El Centro (1940/05/18), Station = El Centro - Imp Vall Irr Dist. Component = 180, (Magnitude M_w = 6.9)	0.350	0.344	0.111	3.381	0.683	0.508	0.068
Treasure Island-Santa Cruz MTNS (Loma Prieta) earthquake (Magnitude M_w = 7.0)	0.332	0.159	0.128	3.189	0.640	0.240	0.068
Petrolia/Cape Mendocino earthquake (1992/04/25) Station = 1023, Component = 270, (Magnitude M_w = 7.2)	0.834	0.422	0.220	6.162	1.412	0.699	0.094

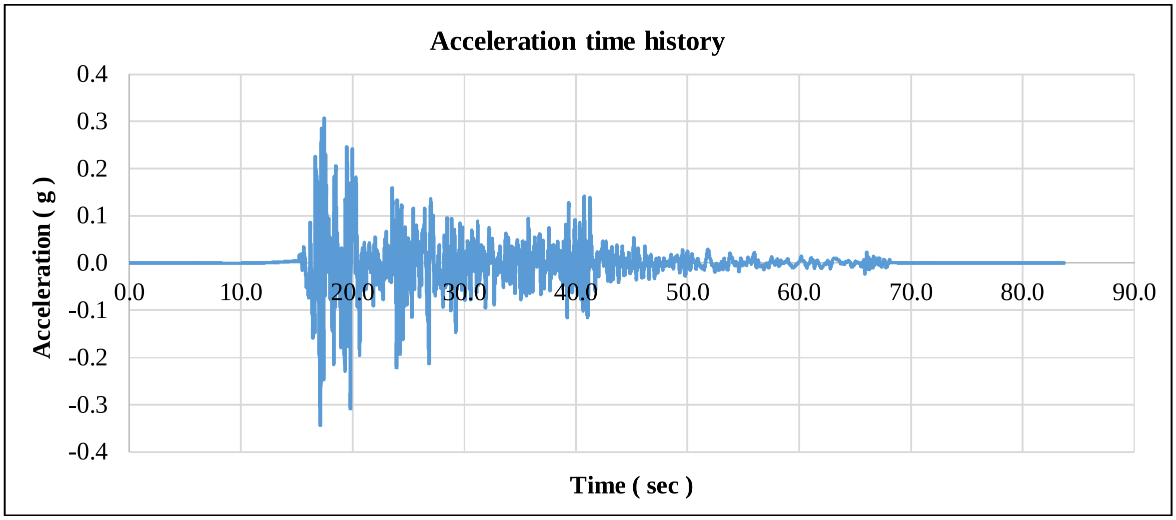


Figure 3. El Centro earthquake–input acceleration time history.

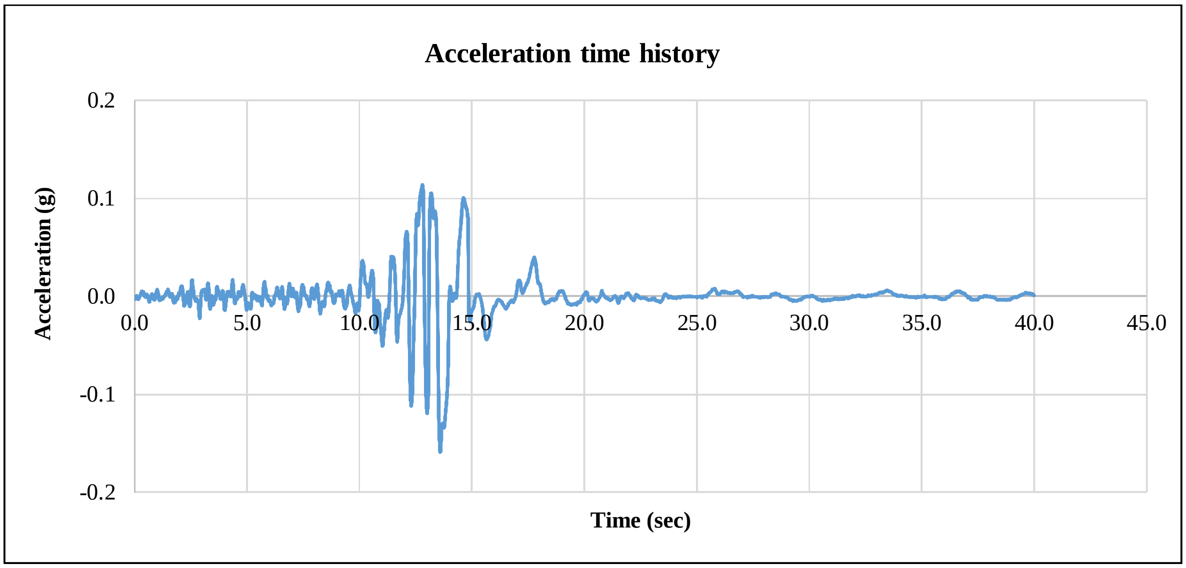


Figure 4. Santa Cruz MTNS (Loma Prieta) earthquake-input acceleration time history.

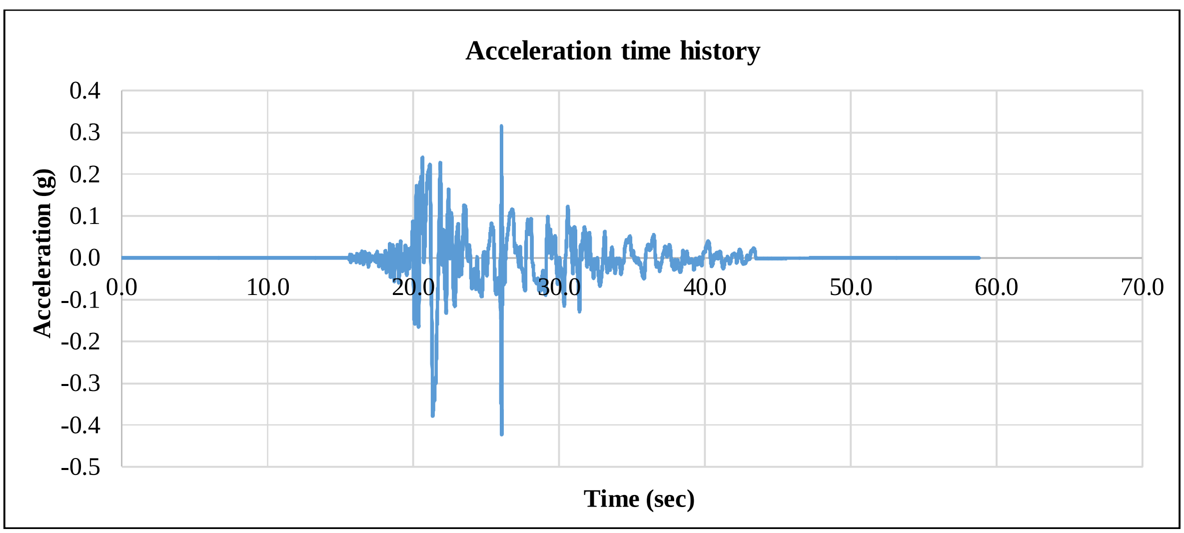


Figure 5. Petrolia earthquake–input acceleration time history.

3. Computation of PGA due to Soil Profiles

The SPT-N values obtained from the borehole data are corrected for necessary overburden and dilatancy corrections. Shear wave velocity of each soil profile are calculated from the standard correlations available in literature. The correlation proposed by Tamura and Yamazaki [24] for all types of soils used in the present study. In addition, this correlation considers the effect of both SPT-N and depth (D) of the soil strata. The acceleration time history of standard earthquake motions of magnitudes varying from 6.9 to 7.2, which are chosen from multi in-built input motions provided in ProShake software, and used for estimation of PGA values by applying each motion at engineering bedrock level. The input peak ground acceleration of El Centro earthquake (6.9 Mw), Loma Prieta earthquake (7.0 M_w), and Petrolia earthquake (7.2 M_w) is 0.344 g, 0.159 g, and 0.422 g, respectively. The standard earthquake motions are compatible with those in Himachal Pradesh, as it has experienced earthquakes of average magnitude 7.0 in past. Earthquake motions of magnitude below 6.5 are not so damaging, hence not considered in the present study. Similar types of successive soil layers in a borehole are grouped together and taken into account as one soil column of a specific thickness with its own unique geotechnical properties, such as shear wave velocity, density, and SPT-N value, and are used as input soil data in ProShake software for estimation of PGA. Software in-built compatible soil models are assigned to each soil column and seismic response of stratified soil deposits in each borehole under the aforementioned standard earthquake input motions generated for all the 181 nos. boreholes spread across the entire studied area. The software computes value of PGA at the center of each soil column in a borehole. The response of each layer with time is depicted in Figure 6.

4. Results and Discussions

SPT tests performed in all the 181 nos. boreholes spread across the entire studied area depicted that the sub-Himalayan district-Hamirpur, and Himachal Pradesh (India) consist of highly variable soil/rock strata at different depths and across the terrain. Density of the soil layers across all sub-divisions is variable with depth and it ranges from 17.30 kN/m^3 to 21.20 kN/m^3. Figure 5 shows typical borehole No. 34 of Nadaun sub-division showing variation of Vs, density, SPT-N and soil columns with depth.

In the Bhoranj sub-division, SPT-N values vary from 8 to 100 with depth and average V_s from 359 to 412 m/s. The soil layers observed were unconsolidated boulders, boulder conglomerate with sandy matrix, clay stone with gravel, boulder and clay, clay with pebbles, clay mixed with boulders, clay mixed with pebbles and boulders, clay with pebble conglomerate, boulder conglomerate, medium-grained saturated silt, dry clay, boulders with clay-sand, and clay with sandy matrix make up the soil strata in sub-division.

In Barsar sub-division, SPT-N values vary from 9 to 100 with depth and average Vs from 362 to 414 m/s. The soil layers observed were soft clay mixed with pebbles, gravels and boulders, clay stone, shale with silt stone, sand stone, conglomerate with sandy matrix, sand stone pebbly, silt, clay, clay mixed with boulders, clay mixed with pebbles, cobbles and boulders, shale with clay stone.

In Nadaun sub-division, SPT-N values range from 11 to 100 across all depths and Vs from 341 to 412 m/s. The soil layers observed were quarzitic boulders with sand, boulders, quarzitic boulders mixed with clay, medium to fine grained saturated silt, clay, sand and pebble, quarzitic sand stone, sand stone, sand mixed with boulders, sand stone cobbles with clay, conglomerate, boulder conglomerate, clay mixed with boulders, and clay mixed with pebbles and boulders.

In Sujanpur sub-division, SPT-N values range from 10 to 100 varies with depth and Vs of soil strata across all depths varies from 359 to 421 m/s. The soil strata observed were: boulders, conglomerate with sandy matrix, boulder with sand, boulder conglomerate, boulders mixed with clay, clay of dry nature, medium grained saturated silt, clay, sand stone, boulders and conglomerates, cemented conglomerate with sandy matrix, clay, pebbles and boulders.

In Hamirpur, sub-division, SPT-N values range from 10 to 100 and Vs varies from 343 to 407 m/s. The soil strata observed were medium-grained saturated sandy silt, fine grained greyish saturated silt, clay, conglomerate of petro nature with sandy matrix, dry clay, sandy clay, conglomerate unconsolidated, conglomerate with sandy matrix, sand stone coarse grained, medium grained sand stone.

The typical borehole's acceleration time history shows that peak acceleration ranged from 0.989 g to 0.909 g, with a predominant time-period between 0.25 s and 0.65 s, as compared to 0.422 g and 1.412 s peak acceleration and predominant time-periods of input motion (Petrolia earthquake, 7.2 Mw), respectively (Figure 6).

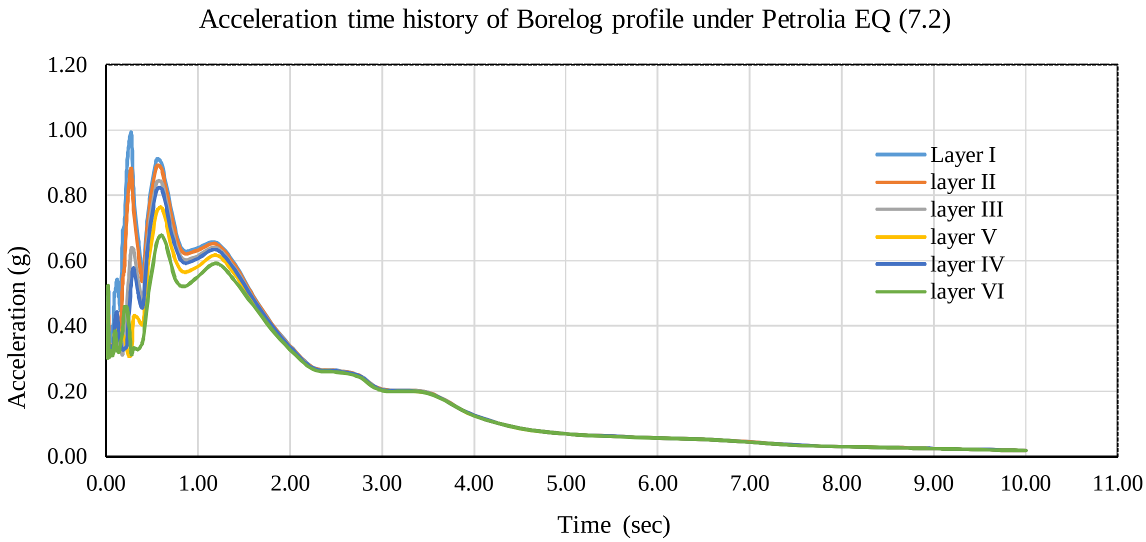


Figure 6. Typical acceleration time history of typical borehole (No. 34) profile of Nadaun sub-division.

Figure 7 (a) to (e) shows the variation of PGA with depth in typical boreholes profile of borehole No. 67, 45, 34, 10, and 101, respectively.

Borehole No. 67 located in Barsar subdivision contains soft clay mixed with pebbles, gravel and boulders having variation of density from 18.40 to 18.80 kN/m^3. Figure 7 (a) represents variation of PGA with depth for borehole No. 67 of Barsar sub-division. The first soil column is of 12 m thickness with 18, 18.50 kN/m^3 and 249 m/s its average SPT-N, density and Vs, respectively. Average SPT-N, density and Vs of second 12 m thick soil column are 43, 18.70 kN/m^3 and 359.00 m/s, respectively. The third soil column is of 6 m thickness with average SPT-N, density and Vs as 68, 18.80 kN/m^3, and 422 m/s, respectively.

Typical borehole No. 45 located in Hamirpur sub-division contains medium-grained saturated silt and dry clay with densities ranging from 18.00 to 18.50 kN/m^3. Borehole No. 45 in Hamirpur sub-division shown in Figure 7 (b) composed of three soil columns. Soil strata in first and second soil column consist of layers of greyish white medium-grained saturated silt up to 24 m depth. 13.50 m thick first soil column has average SPT-N, density and Vs as 17, 18.21 kN/m^3 and 251 m/s, respectively, where as in second soil column its values are 40, 18.4 and 356, and in third column are 46, 18.50, and 393, respectively.

In typical borehole No. 34 of Nadaun sub-division, the densities of the material layers vary from 19.20 to 19.80 and 19.80 to 19.50 kN/m^3 and contain sand mixed with boulders, sand stone, quartzite & cobbles with clay and sand stone & pebbles. Borehole No. 34 of Nadaun sub-division is shown in Figure 7 (c). It has five soil columns. The first soil column has a thickness of 4.50 m, an average SPT-N value of 20, a field density of 19.40 kN/m^3, and average Vs of 220.0 m/s with soft to medium sand mixed boulders of sand stone & quartzite, cobbles with clay as its composition. The second soil column also composed of same material but it is medium to hard having 46, 19.60 kN/m^3 and 315 m/sec its average SPT-N value, field density and Vs, respectively. The third and fourth soil columns are of same strata, i.e. sand stone with its nature hard to very hard; and average SPT-N, Vs and density ranging from 74 to 91, 19.60 to 19.80 kN/m^3 and 373 to 412 m/s, respectively. The fifth soil column consist of very hard sand stone and pebbles with its average SPT-N, Vs and density as 100, 451 m/s and 19.50 kN/m^3, respectively. The last layer represents engineering bedrock level

Typical borehole No.10 located in Sujanpur sub-division contains boulders and loose boulders with densities ranging from 20.30 to 21.20 and 21.20 to 20.05 kN/m^3. PGA keeps on decreasing from ground surface up to 12.0 m depth in typical borehole (10 No.) of Sujanpur subdivision (shown in Figure 7(d) having same type of soil layers up to 12 m depth with SPT-N, density and Vs varies with depth from 19 to 86, 20.05 to 21.20 kN/m^3 and 214 to 373 m/s, respectively. After 12 to 30 m with the change of material from boulder to loose boulders with sand, the density decreases from 21.20 to 20.50 kN/m^3; however N values, and Vs are increasing to 100 and 435.30 m/s, respectively. The overall effect of these soil parameters is reflected in the said figure.

Typical borehole No.101 located in Bhoranj subdivision contain clay with pebbles and conglomerates with densities ranging from 18.10 to 18.50 kN/m^3. Figure 7(e) represents variation of PGA in typical borehole (101 No.) The borehole consists of clay with pebbles conglomerate up to 30 m depth. First soil column is of 10.50 m thickness with average Vs, SPT-N and density as 246 m/s, 19 and 18.30 kN/m^3, respectively. In second soil column (16.50 m thick), average Vs, density and SPT-N values are 368 m/s, 18.40 kN/m^3 and 47, respectively; and in third column (3 m thick), the respective values are 420 m/s, 18.50 kN/m^3, and 63.

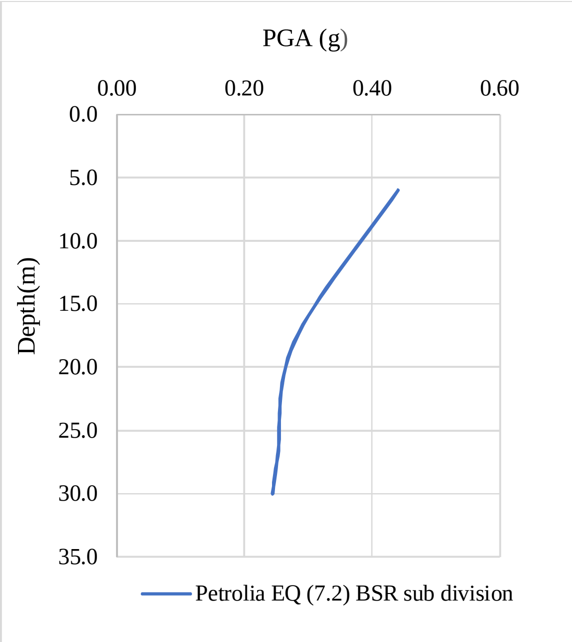


Figure 7 (a). Typical profile of borehole No. 67 (Barsar).

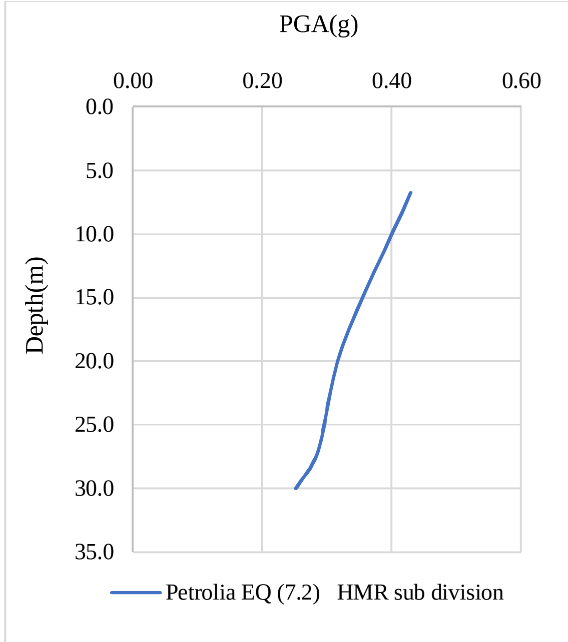


Figure 7 (b). Typical profile of borehole No. 45 (Hamirpur).

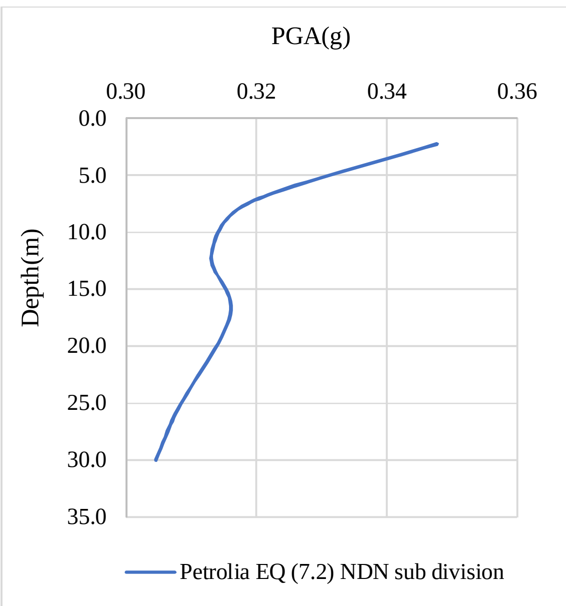


Figure 7 (c). Typical profile of borehole No. 34 (Nadaun).

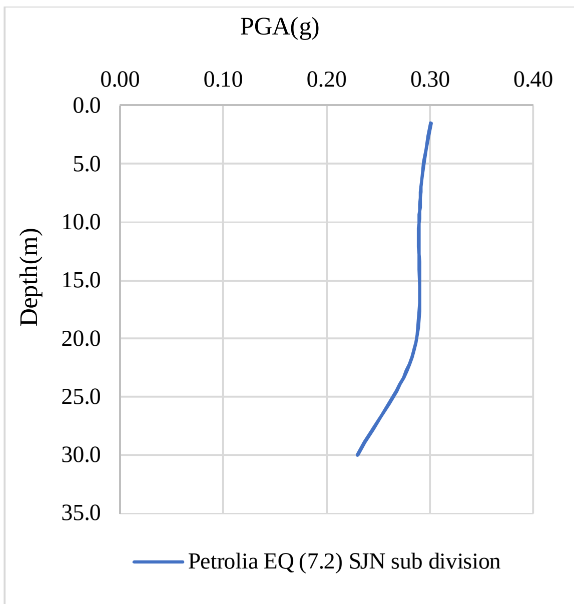


Figure 7 (d). Typical profile of borehole No. 10 (Sujanpur).

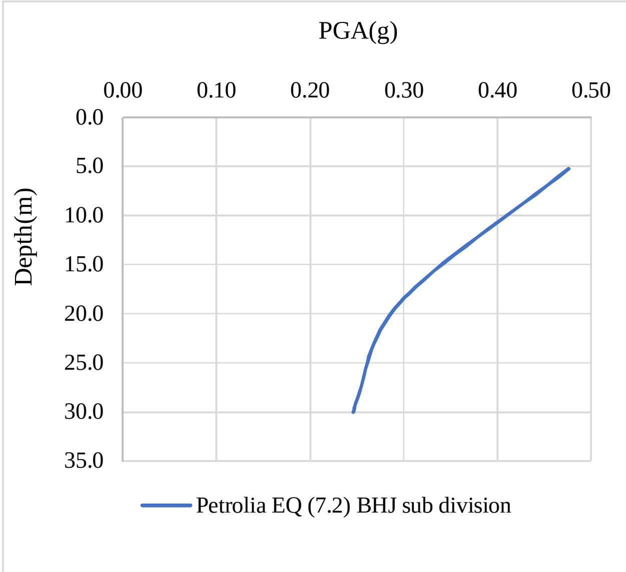


Figure 7 (e). Typical profile of borehole No. 101 (Bhoranj).

The variation of ground motion amplitudes with depth examined using depth plots. The seismic response in terms of PGA has been reproduced for El Centro earthquake, Loma Prieta earthquake, and Petrolia earthquake in 2- and 3-dimensional contour maps corresponding to soil columns at a particular depth (at surface, 10 m, 30 m) are shown in Figures 8 to 13.

Variations in curve observed in Figure 7 (a) to (e) shows that PGA values largely influenced by the composition of the respective soil layer. Hence, it can be observed from the results obtained using one-dimensional software ProShake 2.0 that the denser soil deposits could significantly reduce the site amplification. The earlier studies have noted similar results. [17, 26].

4.1 El Centro earthquake

Figure 8 depicts that PGA values vary from 0.24 g to 0.59 g at the surface; 0.21 g to 0.43 g at 10 m depth; and 0.17 g to 0.29 g at 30 m depth for the 6.9-magnitude earthquake (El Centro) having predominant period and peak acceleration as 0.683 s and 0.344 g, respectively. Figure 8(a) shows PGA maps at ground surface under El Centro earthquake, which reflects higher concentration of PGA values in the region 31.50° N, 76.43° E to 31.65° N, 76.43° E and 31.58° N, 76.73° E to 31.68° N, 76.73 $^\circ$E. PGA values in this region vary from 0.45 g to 0.58 g, which shows amplification of PGA against input motion PGA of 0.344 g. PGA amplification can be seen in other regions also with variation of PGA from 0.34 g to 0.49 g and attenuation in range from 0.29 g to 0.32 g. In Figure 8b), which shows PGA maps at 10 m depth under El Centro earthquake, pattern of PGA response is similar to that at surface. There is a higher concentration of PGA values in the region 31.53 $^\circ$N, 76.53° E to 31.65°N, 76.43°E and 31.55°N, 76.70°E to 31.70°N, 76.68°E, and PGA values are in the range of 0.28 g to 0.43 g. Higher PGA values also vary in the region 31.68° N, 76.30° E to 31.75° N, 76.30° and 31.73°N, 76.48° E to 31.78° N, 76.48° E, ranging from 0.28 g to 0.43 g. In remaining areas, it varies from 0.25 g to 0.34 g. Figure 8(c) shows PGA maps at 30 m depth under El Centro earthquake. PGA ranges from 0.19 g to 0.24 g, which shows attenuation of seismic waves against 0.344 g peak acceleration of input motion. The PGA response pattern is the same at 30 m as it is at 10 m and at the surface, but there is attenuation of PGA against the input motion 0.344 g PGA. The soil strata is highly layered resulting deviations in the response of each bore profile at all depths.

The 3D contours at the surface under the El Centro earthquake shown in Figure 9 depict areas represented by purple and blue colours that do not amplify the PGA and should be preferred for infrastructure construction, while other areas should be avoided. Similarly, the areas represented by PGA peaks in red, yellow, and green at 10 m depth (Figure 9) can be ignored for major construction, and at 30 m depth (Figure 9), there is attenuation of PGA.

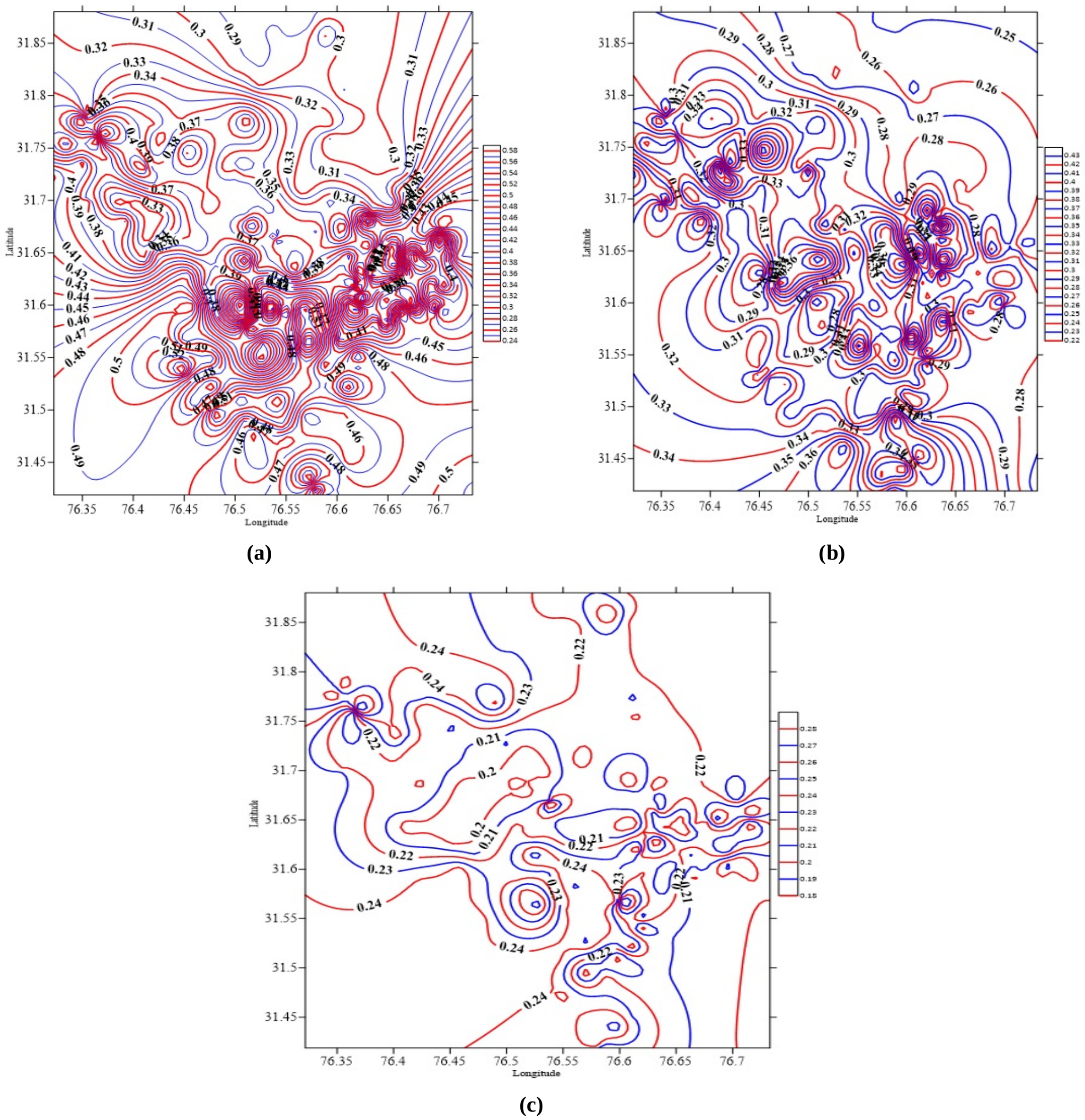


Figure 8. PGA contours for El Centro earthquake: (a) at surface, (b) 10 m depth, and (c) 30 m depth.

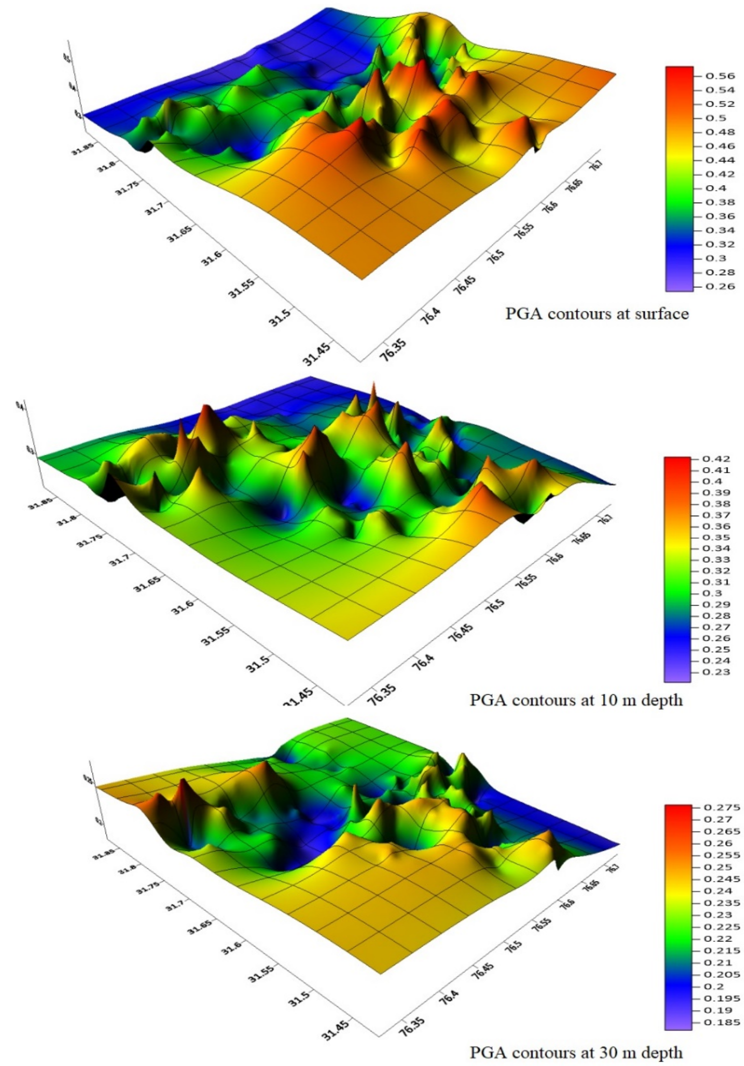


Figure 9. 3D PGA contours at surface, 10 m, and 30 m depth for El Centro earthquake.

4.2 Loma Prieta earthquake

PGA ranges from 0.13 g to 0.25 g at the surface, 0.13 g to 0.22 g at 10 m, and 0.12 g to 0.16 g at 30 m depth for the Loma Prieta earthquake, which had a magnitude of 7.0 with a peak acceleration of 0.159g and predominant period of 0.640 s. Figure 10 illustrate the pattern of amplification. Figure 10(a) exhibits that there is concentration of PGA in region 31.53˚ N, 76.45˚ E to 31.63˚ N, 76.45˚ E and 31.58˚N, 76.73˚ E to 31.68 ˚N, 76.73˚ E. PGA ranges from 0.14 g to 0.24 g in this region. In remaining areas, PGA varies from 0.17g to 0.21g sparsely. Figure 10(b) shows amplification/attenuation pattern of PGA at 10 m depth under Loma Prieta earthquake motion. Concentrations of PGA contours is more in region: 31.53 ˚N, 76.48 ˚E to 31.68 ˚N, 76.48 ˚E and 31.60˚N, 76.73˚ E to 31.68˚N, 76.73˚ E and it varies from 0.16 g to 0.21 g. In other areas, concentration of PGA is sparse and it varies from 0.14 g to 0.18 g. There is attenuation of PGA at 30 m depth under Loma Prieta earthquake input motion as PGA contours are in range of 0.12 g to 0.156 g against the input peak acceleration of 0.159 g shown in Figure10(c).

Under Loma Prieta earthquake, at ground surface the areas represented in purple and blue indicate no PGA amplification shown in Figure 11. Similar is the pattern of PGA amplification at 10m depth (Figure 11) and at 30 m depth (Figure 11), there is attenuation of PGA.

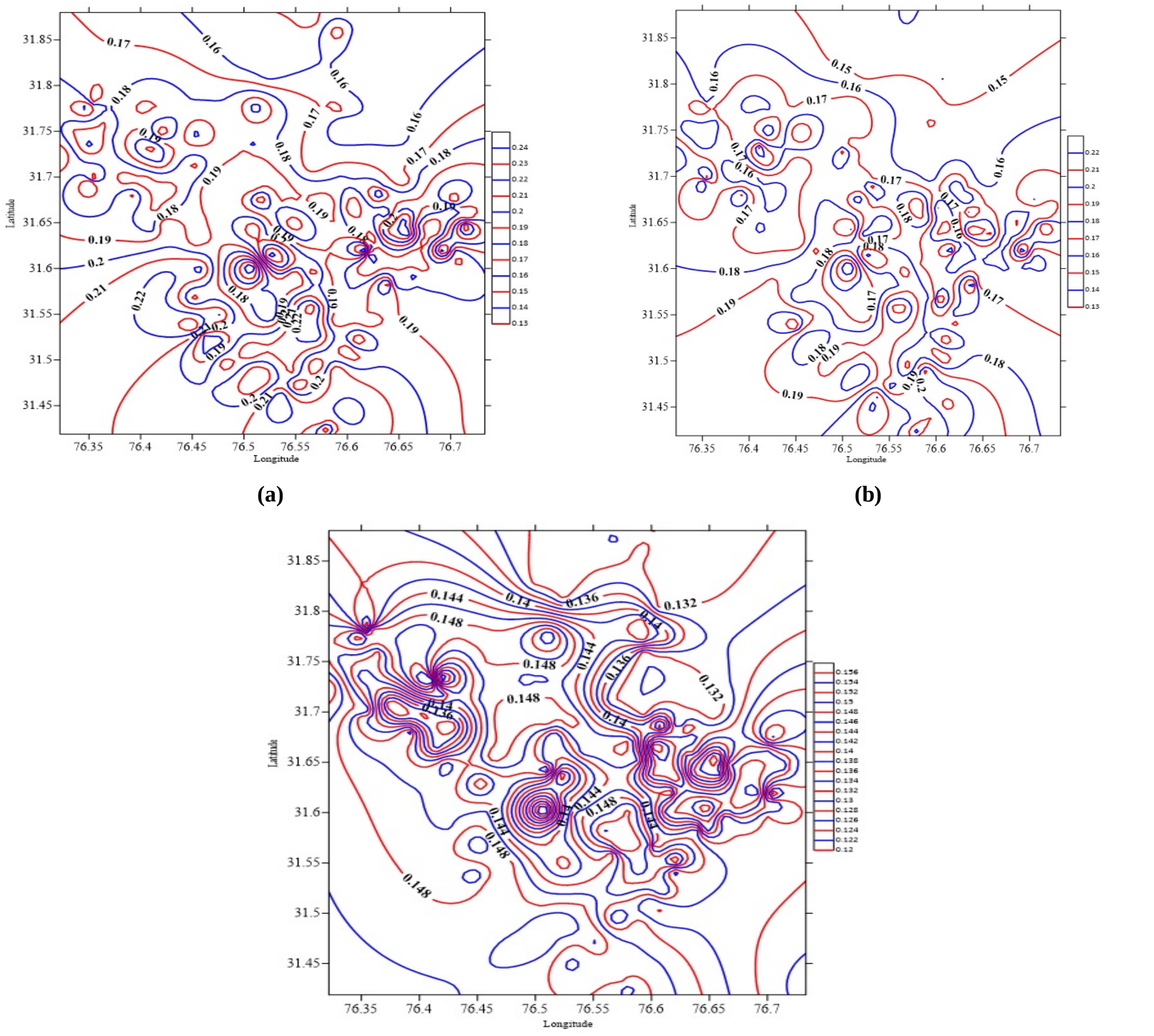


Figure 10. PGA contours for Loma Prieta earthquake: (a) at surface, (b) 10 m depth, and (c) 30 m depth.

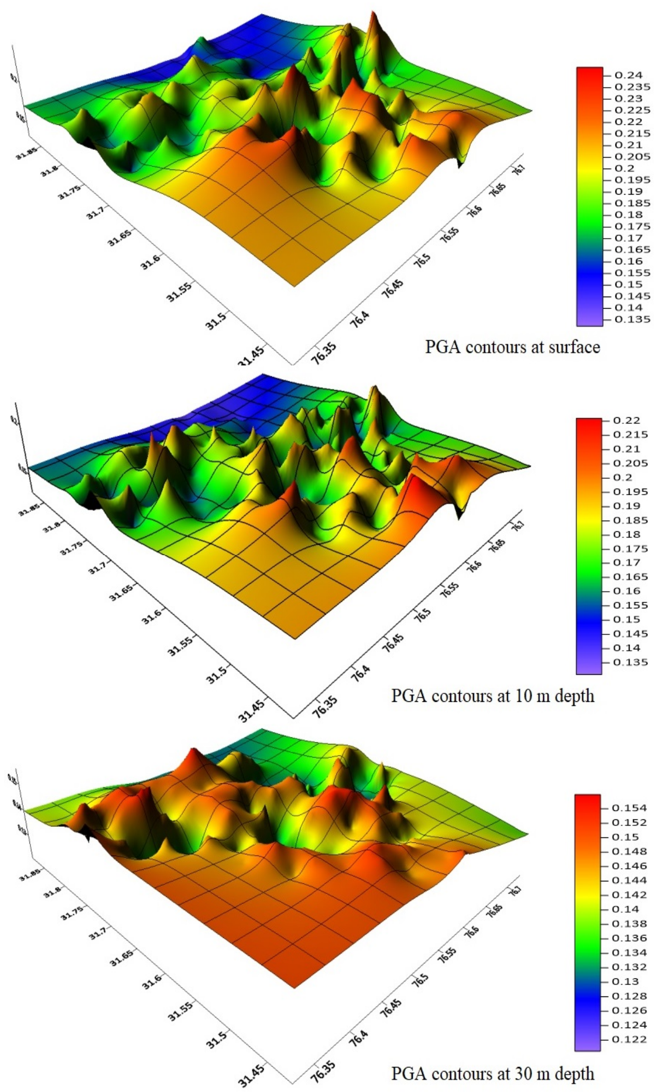


Figure 11. 3D PGA contours at surface, 10 m, and 30 m depth for Loma Prieta earthquake.

4.3 Petrolia earthquake

Similarly, the PGA varies from 0.24 g to 0.72 g at surface, 0.25 g to 0.54 g at 10 m and 0.19 g to 0.36 g at 30 m depth for Petrolia earthquake input motion and shown in Figure 12. Magnitude, peak acceleration and predominant period of the Petrolia earthquake is 7.2, 0.422 g and 1.412 s, respectively.

Figure12 (a) shows PGA amplification at ground surface level under Petrolia earthquake. The concentration of PGA in the area: 31.48° N, 76.45° E to 31.63° N, 76.45° E and 31.60°N, 76.73° E to 31.70°N, 76.73° E, varies from 0.32 g to 0.72 g. In remaining regions, the concentration of PGA contours is sparse and PGA varies from 0.32 g to 0.62 g. In some areas, there is also attenuation of the PGA. PGA amplification/attenuation at 10 m depth under Petrolia earthquake motion shown in Figure 12(b). The PGA contours are more concentrated in region: 31.53° N, 76.48° E to 31.65° N, 76.45° *E* and 31.60°N, 76.73° E to 31.70°N, 76.73° E. PGA contours ranges from 0.26 g to 0.53 g in this region. PGA concentration is also more in region: 31.68° N, 76.30° E to 31.78° N, 76.30° E and 31.70°N, 76.48° E to 31.78°N, 76.48° E with PGA varion from 0.31g to 0.48 g. Figure 12(c) shows attenuation of PGA under Petrolia earthquake motion at 30 m depth.

The color patterns at surface, 10m, and 30m depth (Figure 13) can be used for identification of areas with no or lesser amplifications for infrastructure development even by a common man.

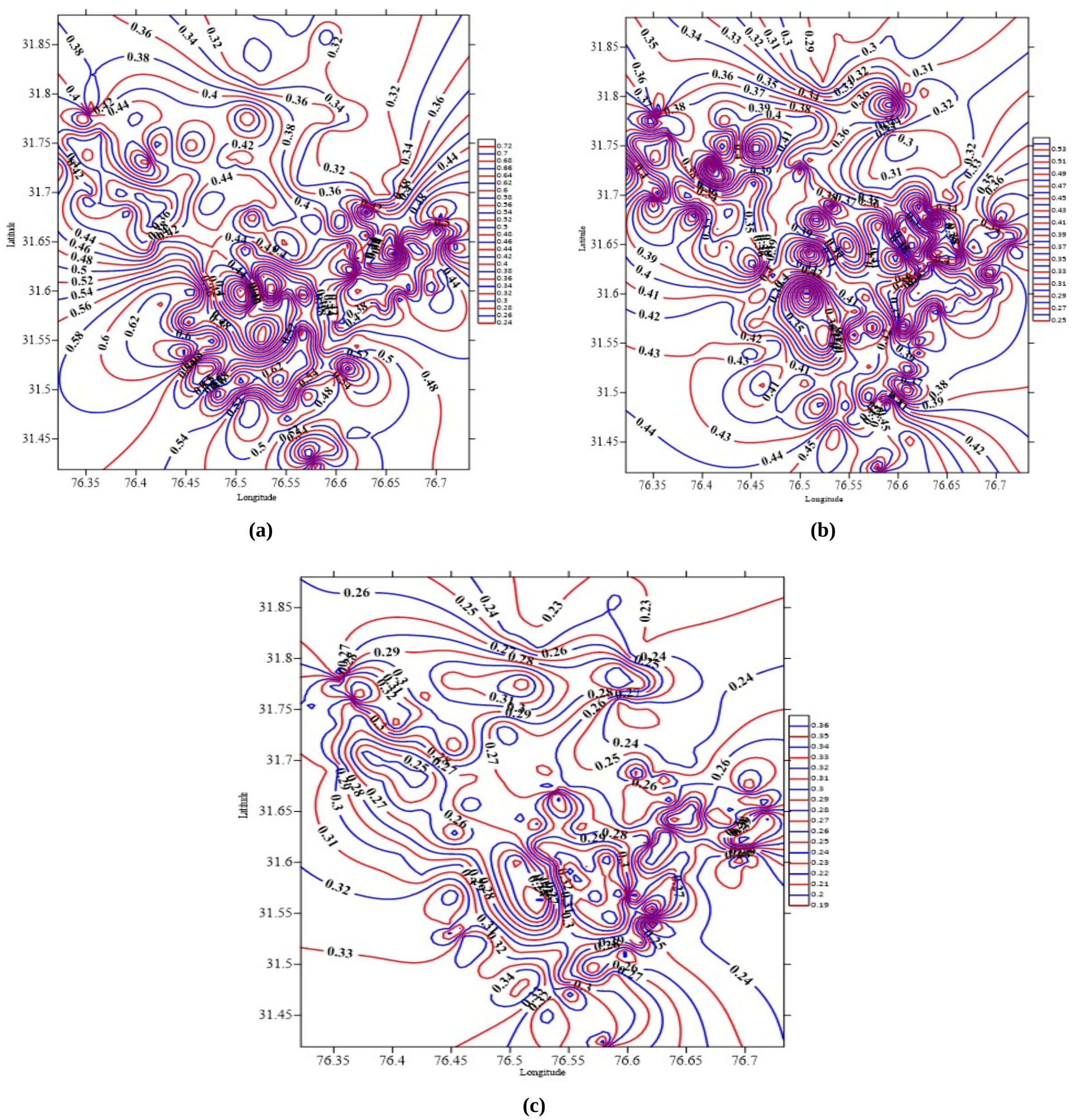


Figure 12. PGA contours for Petrolia earthquake: (a) at surface, (b) 10 m depth, and (c) 30 m depth.

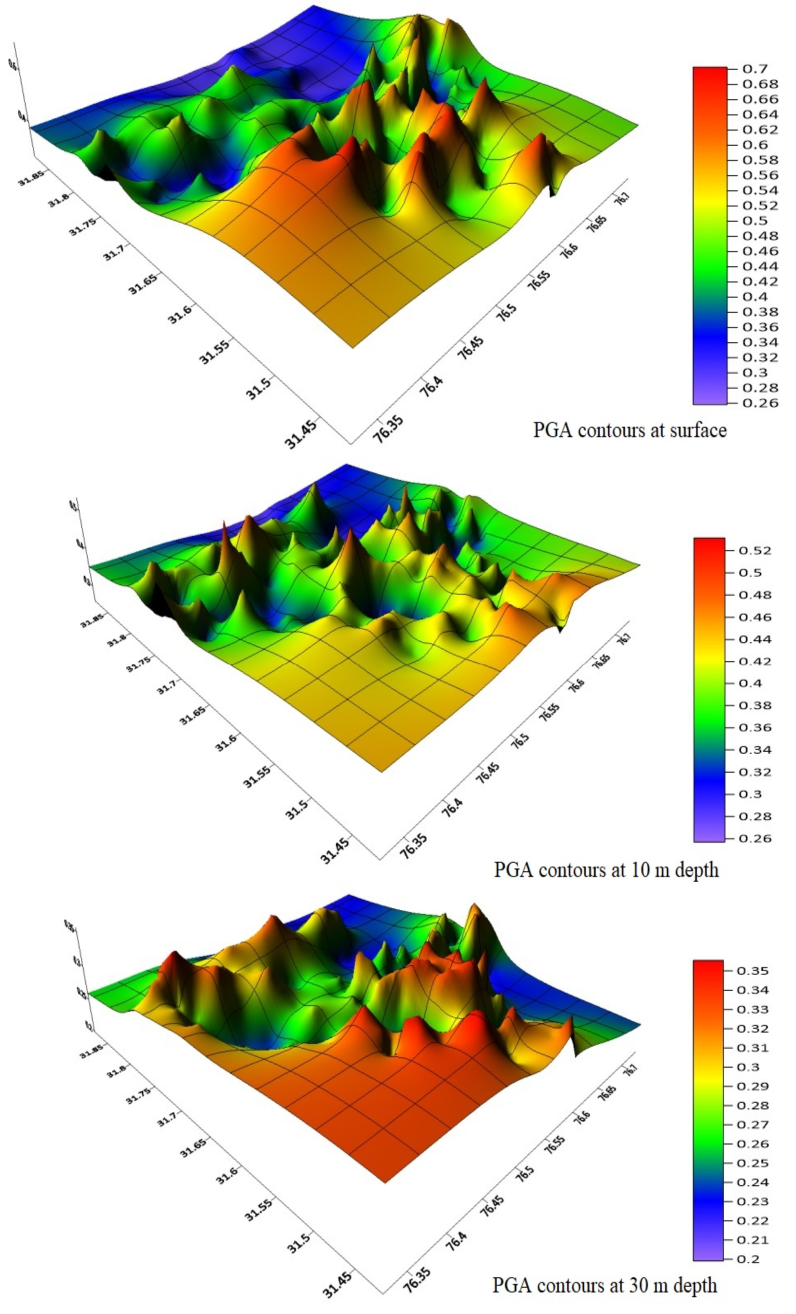


Figure 13. 3D PGA contours at surface, 10 m, and 30 m depth for Petrolia earthquake.

For the planning and construction of important infrastructure, it is best to stay away from the locations mentioned above that consist of a concertation of PGA contours that exhibit motion amplification. Planning and building structures can be done in locations with sparse PGA contours and motion attenuation. There is amplification of PGA at 10 m depth and at surface, whereas there is its attenuation at 30 m depth, which is attributable to hard strata. Variation of strata from moderate hard to soft in range from 10 m depth to ground surface is responsible for amplification of the motion. The foundation of the most of the infrastructures goes maximum up to 10m depth, therefore, even a non-professional can use the PGA maps and the derived information with latitude and longitude as mentioned above with the aid of smart smartphone application for selection of sites for planning and designing of important structures like hospitals, educational institutions and commercial establishments.

6. Conclusions

In the present work, using ProShake 2.0 seismic wave propagation software, site amplifications in terms of PGA variations due to soil layers above engineering bedrock level for 181 locations has been estimated. The considered study area previously experienced an average seismic motion of magnitude 7.0. Three standard earthquake input motion of magnitude 6.9, 7.0, and 7.2 were taken into consideration for the site response studies. The conclusions drawn from the present study are given below:

1) Unconsolidated boulders, boulder conglomerate with sandy matrix, clay stone with gravel, boulder and clay, clay with pebbles, clay mixed with boulders, clay mixed with pebbles and boulders, clay with pebble conglomerate, boulder conglomerate, dry clay, boulders with clay-sand, and clay with sandy matrix are the different soil types found in the Bhoranj sub-division. Average V_s range from 359 to 412 m/s, while SPT-N values range from 8 to 100.

2) The soil strata observed in Barsar sub division consist of soft clay mixed with pebbles, gravels and boulders, clay stone, shale with silt stone, sand stone, conglomerate with sandy matrix, sand stone pebbly, silt, clay, clay mixed with boulders, clay mixed with pebbles, cobbles and boulders, shale with clay stone. SPT-N values of the soil starta varies from 9 to 100 with depth and average V_s from 362 to 414 m/sec.

3) The soil strata observed in Nadaun subdivision consist of Quarzitic boulders with sand, boulders, quarzitic boulders mixed with clay, medium- to fine-grained saturated silt, clay, sand, and pebbles, quarzitic sand stone, sand mixed with boulders, sand stone cobbles with clay, conglomerate, boulder conglomerate, clay mixed with boulders, and clay mixed with pebbles and boulders. SPT-N values of the soil starta ranges from 11 to 100, and V_s from 341 to 412 m/s.

4) Soil strata observed in Sujanpur sub division consist of boulders, conglomerate with sandy matrix, boulder with sand, boulder conglomerate, boulders mixed with clay, dry clay, medium-grained saturated silt, clay, sand stone, boulders and conglomerates, cemented conglomerate with sandy matrix, clay, pebbles and boulders. SPT-N values range from 10 to 100, while V_s of soil strata varies from 359 to 421 m/s.

5) SPT-N values in the Hamirpur subdivision vary from 10 to 100, while Vs values range from 343 to 407 m/sec. The soil strata that were seen were clay, conglomerate of petro-nature with sandy matrix, dry clay, sandy clay, conglomerate unconsolidated, conglomerate with sandy matrix, sand stone, coarse- and medium-grained sand stone, and fine-grained, greyish-saturated silt.

6) From the different earthquake motions, PGA ranges observed for Petrolia earthquake are considered for Hamirpur district as they are higher when compared with El Centro and Loma Prieta earthquake motions. PGA ranges observed for Petrolia earthquake are 0.24 g to 0.72 g at ground surface, 0.21g to 0.54 g at 10 m depth and 0.19 g to 0.36 g at 30 m depth. The range of PGA at ground surface and at 10 m depth may help in excluding the area having its higher concertation/amplification for planning and construction of important structures.

7) Amplification of PGA at 10 m depth and at surface is attributable to moderate hard to soft strata, whereas there is its attenuation at 30 m depth due to hard strata.

8) The predominant time- period for maximum PGA values is in range from 0.25 s to 0.65 s.

The local site conditions play an important role in amplification or attenuation of seismic waves. Peak acceleration and predominant period of input seismic waves in turn also influence the PGA amplification. The estimation of PGA will play an important role in delineating the strata having higher PGA amplification.

Data Availability Statement

All data and models used during the study appear in the published article. The datasets generated during and/or analysed during the current study are available from the corresponding author upon reasonable request.

Conflicts 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.

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References

[1]. Ramakrishnan, M., and Vaidyanathan, R., (2010). Geology of India. Geological Survey of India, Bangalore.

[2]. Prabhu, M. and Raghukanth, S.T.G. (2015). "Development of surface level probabilistic seismic hazard map of Himachal Pradesh." Advances in Structural Engineering, 765-778.

[3]. Bureau of Indian Standards (BIS). Criteria for earthquake resistant design of structures, (IS: 1893:2016, Part I). (www.hpsdma.nic.in).

[4]. Kumar, S. and Narayan, J. P. (2008). Importance of quantification of local site effects based on wave propagation in seismic microzonation. Journal of Earth System Science**.** 117 (2): 731-748 (2008).

[5]. Zeng, X. (1996). A simple procedure to calculate the fundamental frequency of horizontal soil layers. Geotechnique, 46(4), 757-760 (1996).

[6]. Tsuda, K., Steidl, J., Archuleta, R., and Assimaki, D. (2006). Site-response estimation for the 2003 Miyagi-Oki earthquake sequence considering nonlinear site response. Bulletin of the Seismological Society of America, 96 (4A): 1474-1482 (2006).

[7]. Kayen, R.E. and Mitchell, J.K. (1997). "Arias intensity assessment of liquefaction test sites on the east side of San Francisco bay affected by the Loma Prieta, California earthquake of 17 October 1989." Natural Hazards, 16, 243–265 (1997). doi:10.1023/A:10079423250

[8]. Zeevaert, L. (1991). Seismosoil dynamics of foundations in Mexico City Earthquake, September 19, 1985. Journal of Geotechnical Engineering, 117(3), 376–428 (1991). doi:10.1061/(ASCE)0733-9410(1991)117:3(376)

[9]. Boulanger, R.W., Meyers, M.W., Mejia, L.H., and Idriss, I.M. (1998). Behavior of a fine-grained soil during the Loma Prieta earthquake. Canadian Geotechnical Journal. 35 (1): 146-158.

[10]. Narayan, J.P., Sharma, M.L., and Kumar, A. (2002). A seismological report on the 26 January 2001 Bhuj, India earthquake. Seismological Research Letters, 73, 343–355. doi:10.1785/gssrl.73.3.343.

[11]. Govindaraju, L., Ramana, G.V., Hanumantha Rao, C., and Sitharam, T.G. (2004). Site-specific ground response analysis. Current Science. 87 (10): 1354–1362.

[12]. Lebrun, B., Hatzfeld, D., and Bard, P.Y. (2002). Site effect study in urban area: experimental results in Grenoble (France). In Earthquake Microzoning. 2543-2557.

[13]. Tuladhar, R. (2002). Seismic microzonation of the Greater Bangkok with microtremor observations. Ph. D. Thesis, (Asian Institute of Technology, School of Civil Engineering).

[14]. Hasancebi, N., and Ulusay, R. (2006). Evaluation of site amplification and site period using different methods for an earthquake-prone settlement in Western Turkey. Engineering geology. 87 (1-2): 85-104.

[15]. Teramo, A., Maugeri, M., Bottari, A., and Termini, D. (2005). On a quick seismic microzonation of wide areas. Pure and Applied Geophysics. 162 (4): 671-682.

[16]. Kramer, S.L. (2003). Geotechnical earthquake engineering. (Prentice-Hall, New Jersey).

[17]. Trivedi, S.S. (2011). Soil amplification studies for Ahmedabad region. In Int. Conf. Current Trends in Technology, 1-6.

[18]. Shiuly, A., Sahu, R.B., and Mandal, S. (2014). Effect of soil on ground motion amplification of Kolkata City. International Journal of Geotechnical Engineering. 5 (1): 1-20.

[19]. Kumar, A., Satyannarayana, R., and Rajesh, B.G. (2022). Correlation between SPT-N and shear wave velocity (VS) and seismic site classification for Amaravati city, India. Journal of Applied Geophysics, 205, 104757 (2022).

[20]. Boruah, G.K., Baruah, S., Sharma, S., Barua, A.G., and Baruah, S. (2022). Estimation of site-specific amplification factors and expected peak ground motion at Shillong city, Meghalaya: A deterministic approach. Journal of Earth System Science. 131 (2): 1-14 (2022).

[21]. Jena, R., Al-Amri, A., Malulud, K.N.A., Shanableh, A., and Al-Ruzouq, R. (2022). Estimating earthquake peak ground acceleration and intensity using short-time Fourier and wavelet transform techniques: a case study at Odisha, India. Arabian Journal of Geosciences. 15 (11): 1-16.

[22]. Vallianatos, F., and Spingos, I. (2022). A Physical ground for the scaling of Peak Ground Acceleration (PGA) with the integral of squared velocity (I^2Vp) and its potential for Earthquake Early Warning. In Journal of Physics: Conf. Series. 2162 (1): 012018.

[23]. Gupta, K. and Satyam, N. (2022). Estimation of Arias intensity and peak ground acceleration (PGA) using probabilistic seismic hazard assessment of Uttarakhand state (India). Arabian Journal of Geosciences. 1(5): 1-14.

[24]. Tamura, I., and Yamazaki, F. (2002). Estimation of S-Wave Velocity based on Geological Survey Data for K-net and Yokohama Seismometer Network. Doboku Gakkai Ronbunshu, 696, 237-248.value for Jakarta. International Journal of GEOMATE, 7, 980–984.

[25]. Ground response analysis programme Pro Shake 2.0, Edu Pro Civil Systems, Inc. Sammamish, Washington. proshake@proshake.com.

[26]. Thomas, G., and Rangaswamy, K. (2022). Small strain stiffness and site-specific Seismic response of nano-silica stabilized soft clay in Kochi, India: a case study. Arabian Journal of Geosciences. 15 (1): 1-17.

تخمین تقویت حرکت زمین برای اقشار زیر هیمالیا در اثر حرکات زمین لرزه فرضی

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چکیده:

ایالت هیماچال پرادش در غرب هیمالیا (هند) از نظر لرزه‌خیز در مناطق زلزله خیز واقع شده است و هفت ناحیه آن طبق کد لرزه‌ای هند در منطقه لرزه‌خیز V و سایر مناطق در منطقه IV قرار دارند. 90 درصد مساحت منطقه حمیرپور، منطقه مورد مطالعه، در منطقه V قرار دارد. شتاب اوج زمین (PGA) یکی از مهمترین پارامترهای پاسخ لرزه‌ای در طراحی لرزه‌ای سازه است که تا حد زیادی تحت تأثیر ویژگی‌های حرکت لرزه‌ای زیر خاک و ورودی است. در کار حاضر، هدف اصلی شناسایی مناطقی در منطقه است که مستعد تقویت اوج شتاب زمین هستند و می‌توانند برای برنامه‌ریزی زیرساختی مشخص شوند. شتاب اوج زمین یکی از مهمترین پارامترهای مورد استفاده در طراحی لرزه‌ای سازه‌ها است. این با استفاده از برنامه کامپیوتری ProShake تخمین زده می‌شود که در آن پارامترهای خاک از 181 پروفیل گمانه تا عمق 30 متری و حرکات استاندارد داخلی زمین لرزه‌های ورودی 6/9، 7/0 و 7/2 به عنوان پارامترهای ورودی استفاده می‌شود. حداکثر شتاب خروجی زمین از 0/24 گرم تا 0/72 گرم در سطح زمین و از 0/21 گرم تا 0/54 گرم در عمق 10 متر است. اوج شتاب زمین در عمق 30 متری کاهش می‌یابد. تخمین اوج شتاب زمین نقش مهمی در ترسیم استارتا با تقویت شتاب اوج زمین بالاتر خواهد داشت. این اطلاعات می‌تواند به طور موثر برای برنامه ریزی پروژه‌های زیربنایی مهم مانند بیمارستان‌ها، موسسات آموزشی و موسسات تجاری به صورت اقتصادی در منطقه مورد مطالعه مورد استفاده قرار گیرد.

کلمات کلیدی: داده‌های گمانه، آزمون نفوذ استاندارد، سرعت موج برشی، تحلیل پاسخ خطی معادل زمین، شتاب اوج زمین.