High Amplification factor for Low Amplitude Ground Motion: Assessment for Delhi

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Abstract
Building damages as well as induced effects of earthquake are the consequences of surface ground motion at the site. While due importance is given to the soil beneath the ground, the selection of input motion in site response studies is inadequate. Present work highlights the importance of bedrock motion upon the response of a soil column. A typical borehole up to 30m depth is analyzed for wide range of globally recorded bedrock motions in absence of regional ground motion records. Based on the analyses, it is observed that the bedrock motions with low amplitude produce high amplification factors while high amplitude bedrock motions produce low amplification factor.

In seismic microzonation practices of urban centers, the amplitude of bedrock motion and the amplification factor are considered independently for assigning ranks while estimating hazard index. However, from this work, it is found that the amplitude bedrock motion and amplification factor are strongly correlated. Thus, a more combined approach is required while assigning ranks in estimating the hazard index value. In similar way, the correlations between other thematic layers of seismic microzonation practice can be studied in future. Such outcomes will affect the current seismic microzonation practices as well.

Keywords: Site response analysis, bedrock motion, amplification factor, hazard index, seismic microzonation.

Introduction

Earthquake (EQ) generated ground motions are altered at a site due to the presence of local soil available beneath the ground. As a result, a complete change in ground motion characteristics between the bedrock and the surface is observed. Building response as well as induced effects are thus controlled by this changed ground motions. Effects of local soil in controlling the EQ damage were evidenced during 1918 Srimangal EQ in Assam, 1985 Michoacan EQ in Mexico, 1989 Loma Prieta EQ in San Francisco, 1999 Chamoli EQ in Delhi, 2001 Bhuj EQ in Ahmedabad in India, 2005 Kashmir EQ in India, 2011 Sendai EQ in Japan, 2015 Nepal EQ and many more. Detailed discussion suggests failure of geotechnical structures during the 2001 Bhuj EQ. Similarly, during the 1999 Chamoli EQ, even though the epicenter was located in between the lesser and the higher Himalayas, the damages were reported in Delhi and Dehradun located beyond 200km away from the epicenter[23]. Ground shaking due to this event was also felt up to Nepal in the east, Pune in the south-west, Himachal Pradesh and Haryana in the north and Uttar Pradesh & Bihar in the east.[19,23,32]

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Another example of local site effect is the 2011 Sendai EQ (Mw-9.0) located about 130km off the eastern coast of Sendai in the Pacific Ocean. Ground shaking developed during this event triggered liquefaction and differential settlement in the areas of Maihama, Tokai Mura which are located more than 150 km away from the epicenter[26]. On 25th April 2015, the Indian subcontinent was shaken by another EQ event that originated in the Lamjung district of Nepal (Mw-7.8). The epicenter for this event was located 88km away from the city of Kathmandu. However, ground shaking due to the event caused massive failure in Kathmandu including the total collapse of Dharhara tower, Darbar square and various churches in the city.

Induced ground motions were assigned intensity of VIII in the epicentral region and this intensity was felt up to 170km south east of the epicenter. The ground shaking was so severe that intensity of IV was felt in the national capital of Delhi located 850km away from the epicenter. These are few of the classical examples of EQ induced ground shaking causing damages not only concentrated within the epicentral region but also at larger distances due to the presence of local soil. Correct estimation of induced effects of earthquakes depends upon the accuracy in the site response analyses[15]. Due importance is given to the determination of subsoil properties while addressing the local site effects. However, the importance of the selected input motion at bedrock is not highlighted in many of the available site response studies.

In the absence of regional ground motion records, site response studies based on recorded ground motions (1989 Loma Prieta EQ and 1985 Mexico EQ etc;)[15] or synthetic ground motions were attempted by various researchers worldwide. The site response analyses of Kolkata were performed using synthetic ground motion of Peak Ground Acceleration (PGA) 0.163g in absence of recorded ground motions. This value was suggested based on the previous seismic hazard studies of Kolkata. From the analysis, an amplification factor in the range of 4.46 to 4.48 was suggested for the city of Kolkata[15]. Kayen and Mitchell[20] analyzed the data during the 1989 Loma Prieta EQ and showed that the bedrock motion of 0.08g was amplified to the value of 0.29g in the east bay of San Francisco. In another study, the bedrock PHA variation for Chennai was found varying from 0.004g to 0.106g as per Boominathan et al.[8]

However, a single ground motion with PHA value of 0.106g was applied for the entire city without considering the large variation in the bedrock PHA as suggested by seismic hazard studies. Similarly, Ayothiraman et al[5] while determining the liquefaction potential of Guwahati city, used a large number of boreholes considering a surface peak ground acceleration (PGA) value of 0.36g without site response analysis. In another attempt, the liquefaction potential of Guwahati was estimated considering bedrock motion peak horizontal acceleration (PHA) values as 0.15g, 0.19g and 0.25g respectively. However, the bedrock PHA values of 0.36g as per IS1893: 2002 and 0.37g as per NDMA (2010) were suggested for Guwahati. Thus, the bedrock motion selected by Raghukanth and Dash[28] was different from the probable bedrock PHA for Guwahati.

As per Romero and Rix[31], large amplifications corresponding to low amplitude ground motions were observed during 1989 Loma Prieta EQ and 1985 Michaocan EQ. Thus, in case the selected bedrock motion has PHA higher than the probable bedrock PHA as per seismic hazard study, the site response study will underestimate the amplification factor and may underestimate the surface PGA values as well. Seismic microzonation is a broad term which incorporates the effects of earthquake occurrences, both direct as well as the ones induced in rational manner. Local site effect is an important component of seismic microzonation practices and is given due weightage along with bedrock PHA values[15]. As discussed above, the bedrock PHA for Guwahati is close to 0.36g. In an attempt to perform the seismic microzonation of Guwahati[12], the site response analyses were performed by selecting three ground motions having PHA in the range of 0.003g to 0.012g at bedrock level other than 0.36g as suggested earlier. Such a large variation in the two sets of bedrock PHA will have significant effect on the amplification factor and thus the surface PGA.

Highlighting these limitations in ongoing practice, an attempt has been made to study the dependency of the bedrock PHA on site amplification factor. A typical soil column is analyzed for large sets of globally recorded input ground motions.

Study Area

In the present analyses, a typical borehole from shallow deposit in the National capital of India “Delhi” is selected. Delhi has its center at 28.62^{O}N and 77.20^{O}E and is home to approximately 11 million people as per Census 2011. Lying in the north-western part of Indo-Gangetic basin (IGB), Delhi belongs to seismic zone IV as per IS: 1893[17]. In addition to the close proximity of Delhi to the Himalayan belt, a number of regional sources are also lying in and around Delhi namely the Mahendragarh fault, the Delhi Haridwar fault, the Sohna fault, the Delhi Meerut fault and the Rajasthan boundary fault. Iyenger and Ghosh[18] developed the tectonic map for Delhi considering a radial distance of 300 km around the city center. As per Iyenger and Ghosh[18], a total of 13 active sources from Delhi region as well as 7 active sources from Himalayan region can contribute to the seismic hazard of Delhi.

Similar to the work by Iyenger and Ghosh[18], Sharma and Wason performed the seismic hazard analysis of Delhi considering 6 regional sources from around the Delhi region. Existing literature suggests that repeated moderate to severe damages occurred in Delhi due to earthquakes either in the Himalayas or regional earthquakes from nearby sources. Considering the past reported damages in Delhi, the Delhi Disaster Management Authority (DDMA), Government of Delhi reported that there are reports of an EQ even from Mahabharat Era (3000BC). Further, an intensity of IX was reported during 1720 Delhi EQ. Later the 1803 Mathura EQ caused damage to Qutub Minar[39]. These were moderate level of ground motions reported in terms of felt intensity during 1825 EQ, 1830 EQ and 1831 EQ with epicenters near Delhi[6]. Later, during 1956 Khurja EQ moderate damages and injuries were reported in Delhi.

As per Iyenger and Ghosh[18], one of the minarets of Jama Masjid had undergone damage during 1994 EQ. During 1999 Chamoli EQ, the city of Delhi even though was about 280 km away from the epicenter, showed considerable building damages both structural as well as nonstructural. Even during the recent 2015 Nepal EQ, intensity of VI was felt at Delhi. These are clear evidences that the national capital has been undergoing repeated moderate to severe damages since historic times till today. In addition to the codal provisions, a number of regional studies by various researchers are available which focus on the seismic hazard of Delhi and the role of local soil in amplifying the EQ shaking. For the present work, a typical borehole from the north-eastern part of Delhi located close to River Yamuna is selected. As the boreholes were drilled for a client’s based project and not under any research work, the exact location of the site has not been disclosed here.

In-situ subsoil properties

Information on subsoil lithology at the site is obtained based on 41 boreholes of 30m depth each. However, keeping in mind the length of the paper, results considering only one borehole are discussed here. Data of N-SPT values, depth of sample collection and soil type identification etc. are taken from the borelog report. Soil classification in this work is taken directly from the borelog. The typical borelog from the study area is shown in figure 1. It can be observed from figure 1 that surface layer consists of filled up soil. As the depth increases, alternate beds of silty sand (SM) and medium to low compressibility clays (CI-CL) can be found. These soils are available in thickness ranges from 1m to 6m till a depth of 30m below the ground level. Both, the disturbed and undisturbed soil samples were collected at various depths during the borehole drilling as can be seen in figure 1. Depth of water table was reported after 24 hours of observation to ascertain no further variation. As mentioned in figure 1, the water table for BH No 1 is at 0.9m below the ground surface. Plasticity index of the *in-situ* soil (CI-CL) varies between 10% and 24%.

Overall observation by combining all the borelog suggests the presence of silty sand at most of the locations at various depths followed by layers of medium to low compressibility clays. Similar soil type was also reported by Iyenger and Ghosh[18] for northern part of Delhi. Soil characterization as per National Earthquake Hazard Reduction Program (NEHRP) classification system BSSC (2003) using N-SPT values suggests the presence of soft soil (N < 15) up to 4m to 5m below the ground surface. Stiff soil (15 < N < 50) can be found in the depth range of 5m to 15m. At deeper depths (>15m), dense soils (N > 50) are encountered till the depth of 30m. In order to further confirm the layer stratification presented in figure 1, borehole data for Delhi is also collected from other sources. Seismic microzonation of Delhi was attempted by Ministry of Earth Science[25]. Borelog reports as per MoES[25] suggested alternate layers of sand and clay till a depth of 30m and the N-SPT measured were varying up to 83 as per MoES (2014). The subsoil information as per MoES[25] is consistent with the borehole properties presented in figure 1 in this manuscript.

Local Site Effects

Induced effects such as amplified ground motion, liquefaction and landslides are the results of modified ground motion from bedrock to the surface. Classical examples where the presence of local soil enhanced damages include the 1985 Michoacan EQ where the ground motions were amplified up to five times resulting in significant damages in the city of Mexico located about 600km away from the epicenter. Further, the effects of local soil were evidenced during the 1989 Loma Prieta EQ when amplification factor in the range of 2 to 4 was observed in San Francisco-Oakland region located about 120km away from the epicenter[16]. The country of Japan was hit by a great earthquake (Mw-9.0) on 7th April 2011. This was the biggest earthquake ever recorded in Japan causing large amount of liquefaction and uneven settlement in Maihama and Tokai Mura regions located more than 150km away from the epicenter[26].

The 2011 Sikkim EQ (Mw=6.8) caused several buildings to collapse in Mangam, Jorethang and lower Zongue located 150 km away from the epicentre. Ground motions due to 2011 Sikkim EQ were felt at many places in West Bengal and Bihar as well[13]. Recent 2015 Nepal EQ (Mw-7.8) occurred about 80km northwest of Kathmandu. Based on INSAR data, the surface displacement during this earthquake[7] was approximately 2m in the Kathmandu region and caused about 5cm shifts in the border of Nepal towards south. An intensity of VIII on MMI scale was felt up to a distance of 170km south east of the epicenter. The ground shaking due to this event was felt in distant places.

Triggering of avalanches in the areas of Langtang Lirung and landslides in Ghodatabela were reported due to the EQ. The above discussion clearly states that depending upon the subsoil properties, the earthquake induced ground vibrations can cause moderate to large damages even at large distances away from the epicenter. In this work, the response of a borehole from a typical construction site is assessed as a function of input bedrock motion based on equivalent linear site response approach using SHAKE2000[33].

Selection of input motion

Similar to the subsoil data at the site of interest, the input motion is also a pre-requisite for site response analysis. Earthquake induced damages are well documented for prehistoric earthquakes but the ground motion records available are very limited. In the absence of recorded ground motions, selected standard ground motions from EQs such as 1940 El-Centro, 1985 Mexico, 1989 Loma Prieta, 1994 Northridge 1995 Hyogoken-Nanbu and 1999 Chi-Chi etc. have been used in many of the site response studies in India. These motions are directly used or scaled as per required PGA levels. Generation of synthetic ground motions compatible with uniform hazard spectra and hazard values are also followed worldwide for site response studies.[3,6,11,21]

Ground motion characteristics which control the response of the soil include the frequency content, duration and amplitude of the earthquake ground motion. In the absence of regional ground motion records, ground motion characteristics for future EQ at the site of interest cannot be approximated by selecting single ground motion from another region. Thus, a large set of bedrock motions should be considered. These selected ground motions should cover a wider range of amplitude, frequency content and duration.

The study area of Delhi has evidenced EQ shakings due to both nearby and distant sources as discussed earlier. In order to account for this effect, selected ground motions should cover the near field as well as distant ground motion records for the analysis. In the absence of a large dataset of recorded ground motion records in Delhi covering a wide range of ground motion characteristics, a dataset of 30 ground motions recorded globally covering a wide range of ground motion characteristics has been selected in this study. All the data is obtained from PEER database as given in SHAKE2000[34]. Since ground motions considered in this work cover both near field and distant ground motion records, the response of soil column to near field as well as distant EQs can be assessed in this work.

Table 1 presents the ground motion characteristics of all the 30 selected ground motions. It can be seen from table 1 that the frequency content of the ground motion varies from a lowest value of 1.2Hz to a highest value of 50Hz. Similarly, the duration of the selected ground motions is varying from as low as 6.8s to as high as 140s as shown in table 1. The range of magnitude as well as the epicentral distance of ground motion presented in table 1 confirms that both the near field as well as distant EQ records have been considered in the present work similar to the seismotectonics of Delhi. All the selected ground motions are applied at the base of the soil column and the response in terms of amplification factor is assessed for each selected ground motion.

Dynamic soil Properties

The stress-strain behavior of soil is highly nonlinear. The modulus reduction (G/G_{max}) and damping of the soil are the functions of the level of strains and are different for different soil types. In equivalent linear approach, an initial value of shear modulus and damping is assumed which keeps on updating after every iteration to perform the site response analysis. Thus, the soil response is a function of the G/G_{max} and damping properties of the soil. These G/G_{max} and damping ratio curves for each of the materials are obtained from laboratory tests such as simple shear, torsional shear, cyclic triaxial and resonant column tests[37]. Due to limited resources such curves on regional level are not available. However, certain standard curves based on a large number of tests are available for various soil types.

For the present work, three types of soils are considered as presented in figure 1. These include silty sand, low compressibility clays and medium compressibility clays. Since the client recommendations were not to place foundation in the fill layer, this layer has not been modelled in the analyses. Thus, three types of soils are considered from the SHAKE2000 database as 1) Average sand for silty sand; 2) Clay with PI ranges from 0 to 10 for low compressibility clay and 3) Clay with PI ranges from 10-20 for medium compressibility clay. G/G_{max} and damping curves for sandy soil given by Seed and Idriss[35] are used for silty sand layers. Similarly, Sun et al[38] studied G/G_{max} ratio of clay with different PI with over consolidation ratio (OCR) in the range of 5 to 15. Sun et al[38] proposed G/G_{max} for various clays and found that low value of PI has considerable effect on the position of G/G_{max} curve compared to high PI clays. For this reason one damping curve as per Seed and Idriss[35] is used for both the clays (CI and CL).

Based on SPT values, soil below 30m depth is found very dense and thus G/G_{max} and damping curves for very dense soil proposed by Schnabel[34] are used with reference to earlier published work[10,22]. For present work, G/G_{max} curve for clay soil as per Sun et al[38] is used. The average damping curve for clay is independent of PI of the clay. Based on SPT values, soil below 30m depth is found very dense and thus G/G_{max} and damping curves for very dense soil proposed by Schnabel[34] are used with reference to earlier published work.[10,22,30] Selected damping curves and the G/G_{max} for various soil types in this work are shown in figure 2.

Analysis and Results

In order to perform equivalent linear analyses using SHAKE2000, a soil column is generated considering the sub-soil properties of the selected borehole as discussed above. *In-situ* densities and the thicknesses of various layers are modelled. Layers with thickness > 3m are subdivided into 3m thickness sublayers. N-SPT values obtained from the *in-situ* test are used to determine the shear modulus of each soil layer. For the estimation of shear modulus (G_{max}), built correlation between G_{max} and N-SPT inSHAKE2000 is used in the present analysis. At present no correlation between G_{max} and N-SPT is available for Delhi. For this reason the built empirical correlation in SHAKE2000, originally proposed by Seed et al[35] is adopted.

The suitability of built correlation for Delhi soil has been done in two steps. In the first step, the empirical correlation between shear wave velocity (Vs) and N-SPT for Delhi as per Rao and Ramana[29] is compared with the correlation proposed by Ohsaki and Iwasaki[27]. Figure 3 shows that the comparison between the two correlations is matching very well for the entire range of N-SPT. This indicates that the characteristics of soils used in developing these two correlations are very similar. In the second step, correlation between G_{max} and N-SPT developed by Ohsaki and Iwasaki[27] was compared with the built in correlation in SHAKE2000 proposed by Seed et al[35]. Figure 3 shows that both the correlations between G_{max} and N-SPT are closely matching for the entire range of N-SPT.

Combining the observations from the above two steps indicate that the built correlation in SHAKE2000 for the estimation of G_{max} can be used confidently for the present study. Further, soil deposit below 30m depth is modelled as elastic half space with dynamic properties of very dense soil as discussed above. The soil column is subjected to all the selected 30 input ground motions and the responses in term of amplification factors are observed. Since the present work is to understand the bedrock PHA versus amplification factor variation, the surface PGA for each input motion is observed from the output. Further, these surface PGA values are used to determine the amplification factor corresponding to each ground motion. The variation of amplification factor versus PHA for the borehole presented in figure 1 obtained from the above analysis is given in figure 4.

It can be observed from figure 4 that higher values of amplification factors are corresponding to very low value of PHA. Further, with increase in the PHA values, there is considerable reduction in the amplification factor values. High amplification factors for ground motions with low PHA are the attributes of nonlinear soil behaviour. As per Romero and Rix[31], large accelerations are the attributes of large strains. At large strains, the soil response is governed by its very high damping ratio. As a result, there will be low amplification in the ground motion compared to input motions with low acceleration.

Large amplifications corresponding to low amplitude ground motions reported above were also observed during 1989 Loma Prieta EQ and 1985 Michaocan EQ as reported by Romero and Rix[31]. In order to validate the above findings, comparisons are made with the existing literature. EPRI[14] presented the variation in the amplification factor values in the PHA range of 0.05g to 1.25g. Comparison of present results with EPRI[14] shows that the present findings are closely matching with the EPRI[14] findings as shown in figure 4. For PHA <0.05g, present work shows very high values of amplification factor. Since EPRI[14] does not cover PHA <0.05g, study performed by Ashford et al[4] is used in the present work for comparison. It can be seen from figure 4 that for PHA<0.05g, higher values of amplification factor obtained from the present analysis are matching very closely with the finding of Ashford et al[4]. Thus, overall it can be said that the variation in the amplification factor obtained from the present analyses is matching very well with the existing literature.

Based on the variation pattern shown in figure 4, it can be said that for same soil column, for PHA range of 0.03g to 0.08g, there is drastic variation in the amplification factor. Further, in the PHA range of 0.08g to 0.22g, the amplification factor is varying at a slower rate compared to the previous trend and for PHA greater than 0.22g; there is further reduction in the rate of amplification factor variation. This plot clearly highlights that even though the local soil is altering the input motion, the rate of alteration is significantly influenced by the input motion. For the same soil column a soil site will experience more amplification when subjected to low PHA ground motion compared to ground motion with higher PHA value.

In seismic microzonation practises, both the bedrock PHA as well as the amplification factor are given due importance separately while estimating hazard index. A higher rank to higher value of PHA is assigned since it is causing high seismic hazard to the site. Similarly, a high value of amplification factor is assigned higher rank since it is causing more amplification in the bedrock motion. In seismic microzonation practises, assigning ranks to PHA and the amplification factor are attempted independently. For the seismic microzonation of National capital, Delhi, bedrock PHA and the amplification factors are assigned ranks independently as per MoES[25] while determining the hazard index value. Similarly, for the seismic microzonation of Bangalore as well, the ranks to PHA as well as amplification factor are assigned independently as per MoES[24].

In another attempt to perform the seismic microzonation of Lucknow, Abhishek[1] assigned ranks to the values of PHA as well as amplification factors independently. In the present analysis however, as shown in figure 4, the values of PHA and amplification factors are found related to each other such that higher values of amplification factors are corresponding to low PHA values only and vice versa. The range of PHA and the corresponding range of amplification factor for above three categories are presented in table 2. In addition, the ranks to each range of PHA and the amplification factor are also given in table 2.

It can be observed from table 2 that ranks to both PHA and the amplification factor are interrelated This clearly indicates that ranks assigned to both the PHA as well as the amplification factor should be considered in a more combined manner while estimating the hazard index value. In addition, both PHA and the amplification factor cannot have a high rank simultaneously. Seismic microzonation of urban centre utilizes various thematic layers in determining hazard index values including the PHA and the amplification factor. In the present work the interrelation between the PHA and the amplification factor has been studied. In a similar way, the correlation between other thematic layers such as PHA, average shear wave velocity, depth to overburden etc. can be studied in future to provide a more rational approach in estimating the hazard index values.

Conclusion

Local site effects play an important role in deciding the level of ground shaking. Present work is an attempt where the dependency of the soil response on the input motion is assessed. Large sets of globally recorded ground motions are selected covering a wide range of ground motion parameters representing both the nearby and distant sources of seismic hazard for the site under consideration. Based on the equivalent linear approach, site response analyses are performed for a typical site. From the analyses, it is found that soil columns subjected to input motions with low PHA values will have high amplification factor in comparison to the same soil column if subjected to input motion with a high PHA. These findings are in accordance with the available literature.

From the present analyses, the rate of change in amplification factor is found to be very high for PHA<0.08g, intermediate for 0.08g<PHA<0.22g and low for PHA>0.22g. In the present seismic microzonation practices, among various thematic layers, the PHA and the amplification factors are assigned ranks independently. However based on the present work, it is found that the above two parameters are strongly interrelated. In addition, high values of PHA and amplification factor are not possible simultaneously. Thus, a more combined approach while estimating the hazard index is needed. In the present work, the dependency between two thematic layers namely the PHA and the amplification factor is studied. Correlation between other thematic layers such as average shear wave velocity and depth of overburden can be studied in future.

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BH	Ground Water Table at 0.9m below Ground Level (GL)						
Depth below GL(m)	Soil Description	Thickness of Layer (m)	Legend	Soil Classification	Sample	Depth (m)	SPT-N values
1.0	Fill	1.0		-	-	1	2
2.0	Silty Sand	1.0		SM	UDS	2	4
3.0	Low Compressibility Clay	1.0		CL	SPT		
4.0					SPT	3.5	8
5.0					SPT	5	14
6.0					SPT	6.5	18
7.0					UDS		
8.0					SPT	8	22
9.0	Silty Sand	6.0		SM	UDS		
10.0					SPT	9.5	24
11.0	Medium				SPT	11	26
12.0	Compressibility Clay	2.0		CI	SPT	12.5	33
13.0					UDS		
14.0					SPT	14	37
15.0					SPT	15.5	45
16.0					UDS		
17.0					SPT	17	55
18.0					SPT	18.5	62
19.0					UDS		
20.0	Silty Sand	8.0		SM	SPT	20	71
21.0					SPT	21.5	66
22.0					UDS		
23.0	Medium				SPT	23	69
24.0	Compressibility Clay	4.0		CI	SPT	24.5	79
25.0					UDS		
26.0					SPT	26	84
27.0	Silty Sand	3.0		SM	SPT	27.5	95
28.0					UDS		
29.0	Medium				SPT	29	96
30.0	Compressibility Clay	3.0		CI	SPT	30	101

Note Borehole terminated at 30.0 m
DS-Disturbed Sample SPT-Standard Penetration Test
UDS-Undisturbed Sample

Figure 1: Typical Borehole from the site

Table 1
Ground Motion properties of the selected input motions

S. N.	Ground Motion Details as per SHAKE 2000	Epicentral Distance (km)	Magnitude	PGA (g)	Duration (s)	Predominant Frequency (Hz)
1	ADAK, ALASKA 1971-M 6.8;R-67KM, N81E	86.77	6.8	0.098	24.58	8.33
2	ANCHORAGE, ALASKA 1875, M-6, R81-GOULE HALL STATION	81.93	6.0	0.036	18.59	10.00
3	ANCHORAGE ALASKA 1975, M 6, R 79, WESTWARD HOTEL STATION (BASEMENT)	78.37	6.0	0.049	38.96	7.14
4	ANZA 02/25/80, BORREGO AIR BRANCH 225	43.1	5.3	0.046	10.25	3.85
5	ANZA 02/25/80 1047, TERWILLIGER VALLEY 135	15.8	5.3	0.080	10.01	16.67
6	BISHOP-ROUND VALLEY 11/23/84 1914, MCGEE CREEK SURFACE 270	42.35	5.8	0.075	6.80	12.50
7	BORREGO MOUNTAIN 04/09/68 0230, EL CENTRO ARRAY 9, 270	60.0	6.4	0.056	39.95	39.95
8	BORREGO MOUNTAIN 04/09/68 0230, PASADENA-ATHENAEUM, 270	216.8	6.4	0.009	60.23	1.22
9	BORREGO MOUNTAIN 04/09/68 0230, TERMINAL ISLAND, 339	205	6.4	0.008	51.80	2.50
10	CAPE MENDOCINO EARTHQUAKE RECORD 04/25/92, MW-7.0, 90 DEG COMPONENT	10.0	7.1	1.03	59.98	50.00
11	CHALFANT 07/20/86 1429, BISHOP PARADISE LODGE,070	19.8	6.4	0.046	39.95	16.67
12	CHILE EARTHQUAKE, VALPARAISO RECORD, 3/3/85	129.2	7.8	0.120	79.39	16.67
13	COALINGA 05/02/83 2342 PARKFIELD, FAULT ZONE 6/ 090	43.9	6.5	0.055	39.95	8.33
14	COALINGA 05/09/83 PALMER AVE ANTICLINE RIDGE, 090	12.5	5.3	0.215	40.00	10.00
15	GEORGIA, USSR 06/15/91 0059, BAZ X	49.0	6.2	0.033	34.07	4.55
16	IMPERIAL VALLEY 10/15/79 2319, BONDS CORNER 230	15.9	5.0	0.100	19.885	5.56
17	KERN COUNTY 7/21/52 11:53, SANTA BARBARA COURTHOUSE 042	80.5	7.5	0.086	75.35	4.17
18	KOBE 01/16/95 2046, ABENO 000	24.9	6.9	0.22	139.98	5.00
19	KOBE 01/16/95 2046, KAKOGAWA 000	22.5	6.9	0.250	40.91	12.50
20	KOBE 01/16/95, KOBE PORT ISLAND 090	0.9	6.9	0.530	42	2.50
21	LIVERMORE 01/27/80 0233, HAYWARD CSUH STADIUM 236	33.9	5.8	0.027	15.98	3.13
22	LIVERMORE 01/27/80 0233 LIVERMORE MORGAN TERR PARK 265	20.6	5.8	0.197	24	5.56
23	LOMA PRIETA TA 10/18/89 00:05, ANDERSON DAN DOWNSTREAM 270	16.9	7.0	0.240	39.59	5.00

24	LOMA PRIETA TA 10/18/89 00:05, HOLLISTER DIFF ARRAY 255	13.9	7.0	0.270	40	1.92
25	MICHIOACAN EARTHQUAKE 19/9/85, CALETA DE CAMPOS, N-COMPONENT	38.36	8.1	0.140	81.06	2.27
26	NORTHERN CALIFORNIA 09/22/52 1141, FERNDALE 134	44.3	5.2	0.070	40	5.00
27	NORTHRIDGE EQ 1/17/94 1231, ANACAPA ISLAND	71.4	6.7	0.013	40	25.00
28	NORTHRIDGE EQ 1/17/94 1231, ARLETA 360	9.5	6.7	0.310	39.94	16.67
29	PARKFIELD 06/28/66 04:26, CHROME # 8	11.2	6.1	0.116	26.09	25.00
30	TRINIDAD 11/08/08, 10:27, RIO DEL OVERPASS E	72.0	7.2	0.130	22	3.13

Table 2
Range of amplification factor corresponding to bedrock PGA

Range of bedrock PHA (g)	Ranks of bedrock PHA	Range of Amplification factor (AF)	Ranks of AF
0.03-0.08	1	7.5-2.7	3
0.08-0.22	2	2.8-2.2	2
0.22-0.53	3	2.2-1.0	1

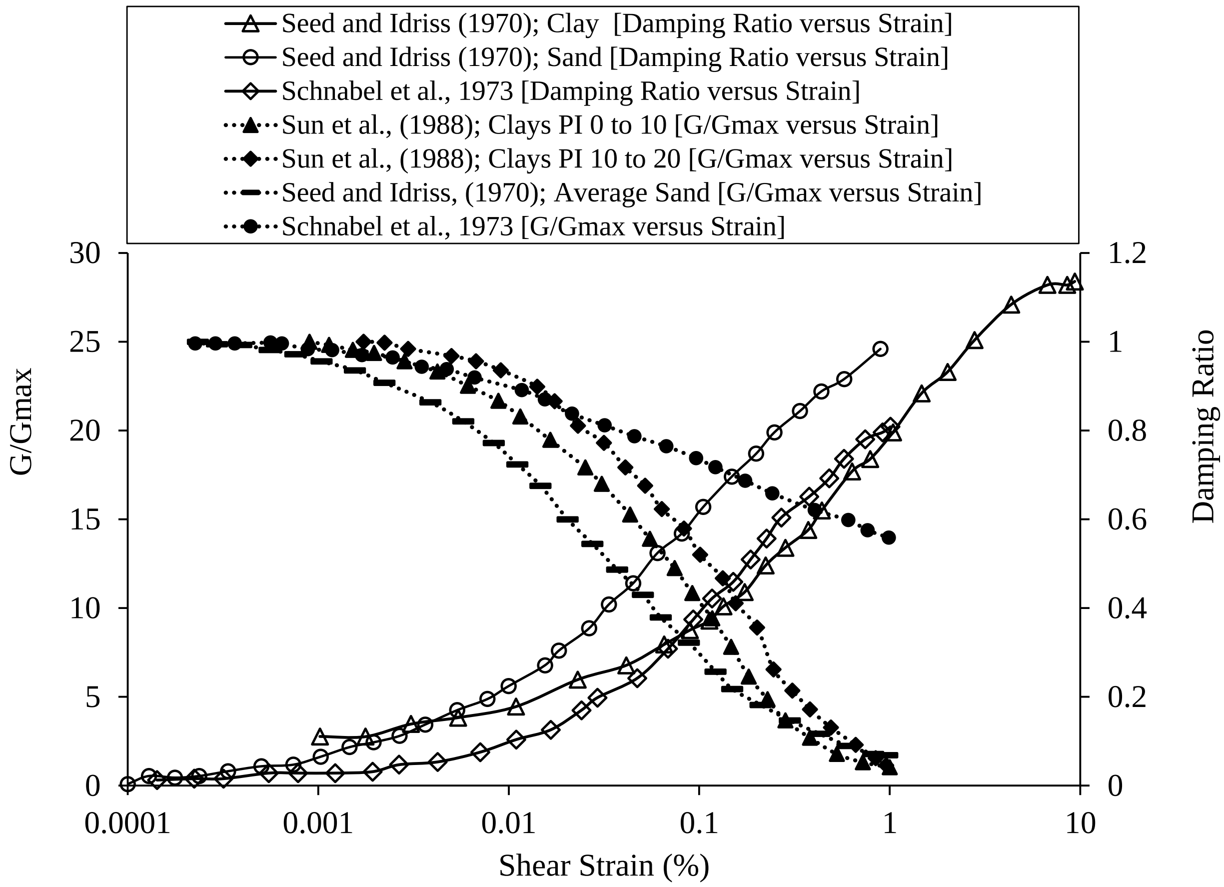

Figure 2: Dynamic properties of selected soils

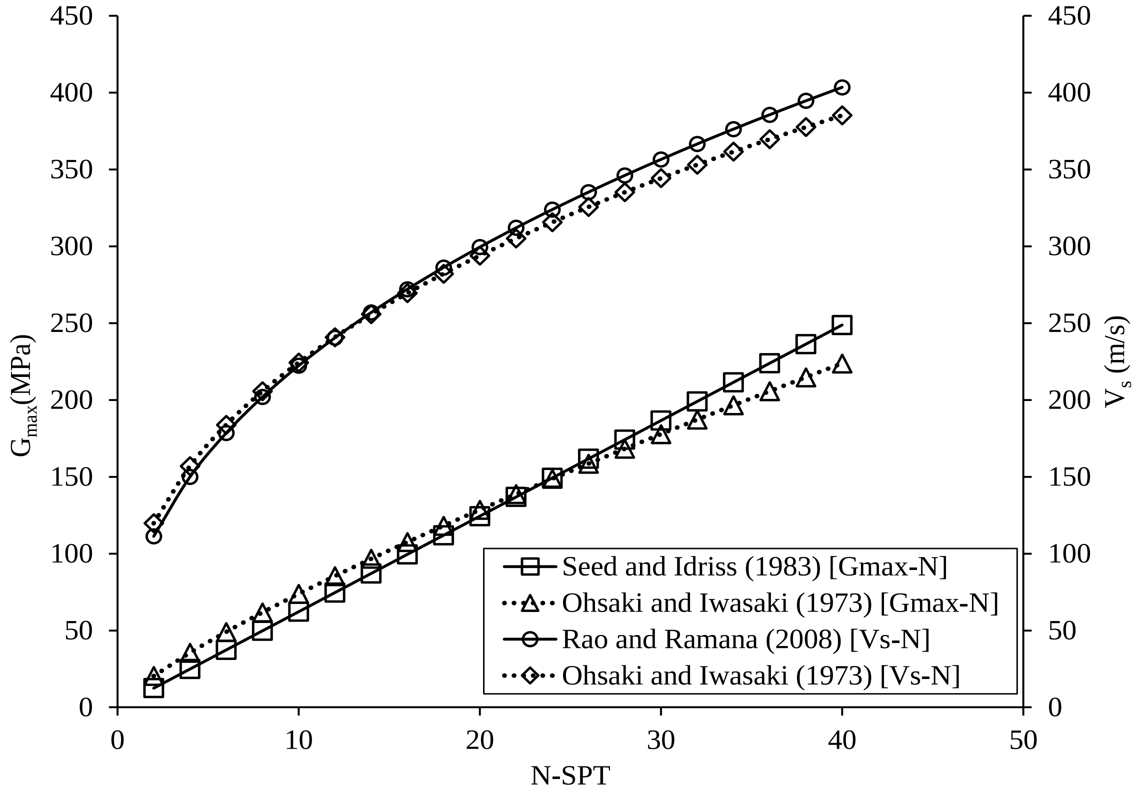

Figure 3: Comparison between Vs versus SPT-N and G_{max} versus SPT-N for the present work

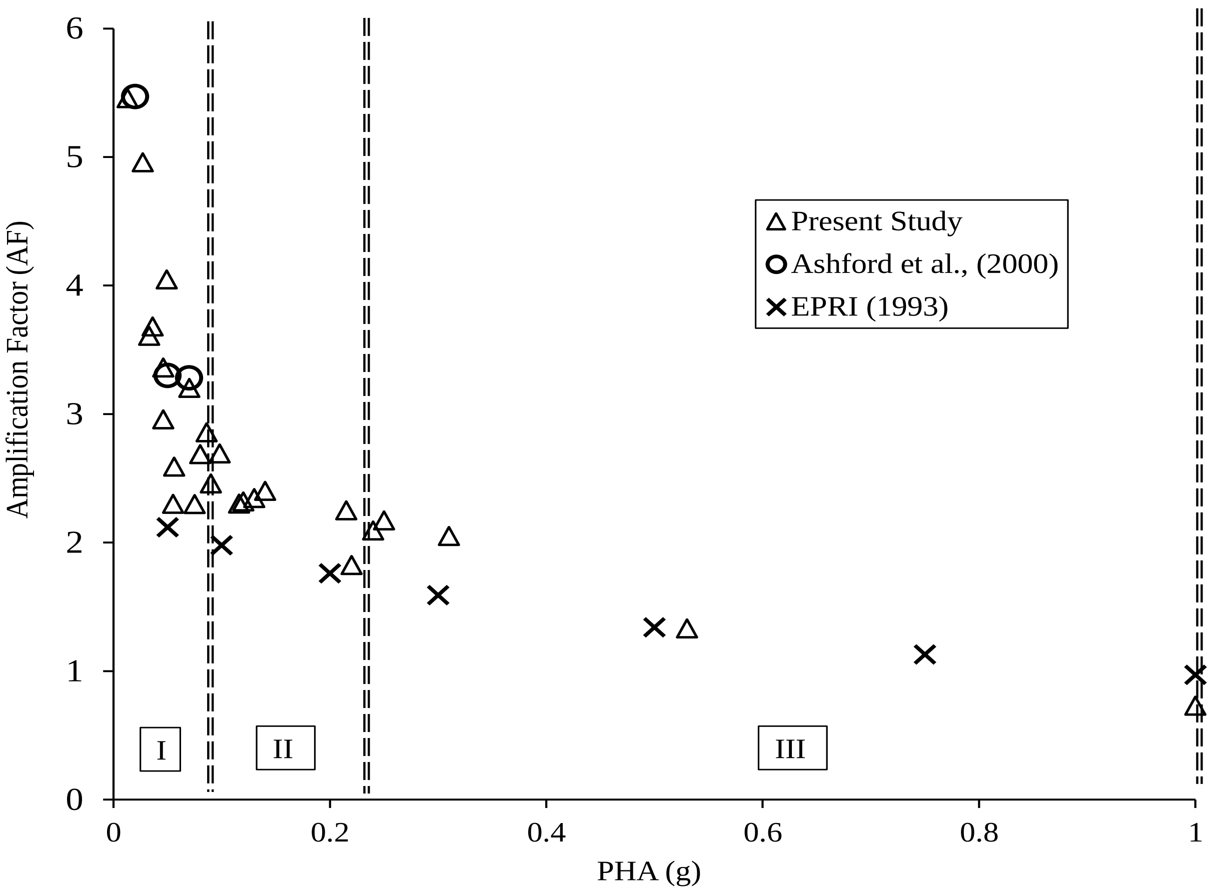

Figure 4: Variation of amplification factor versus PHA

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