SITE RESPONSE ANALYSES OF SHALLOW BASINS BASED ON GLOBAL RECORDS AND DATA FILTERING TO ARRIVE AT THE CODAL RECOMMENDATIONS

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ABSTRACT:
Destructive earthquake across the globe have highlights various possible form and extent of damages during moderate to major size earthquakes. Subsoil properties play a vital role in controlling actual damage scenario. Induced effects such as liquefaction and landslide are also the function of surface ground shaking. In the present work, site response analysis based on equivalent linear model using SHAKE2000 are attempted to assess surface scenario. To assess the liquefaction potential of the site, globally recorded ground motions from PEER database are considered. Site response results show a wide variation in amplification factor and thus, posts filtering of the analyses results have been attempted for the first time in this work. Revised data show a narrow range of surface PGA which matches well with the earlier published literature as well as close to codal provisions.

Keywords: induced effects, site response analysis, equivalent model, surface PGA.

1. INTRODUCTION

Frequent earthquakes are happening in different regions of India starting from seismically highly active regions such as the North-East India and the Himalayan belt to low seismicity regions such as the Peninsular India. Heavy construction of infrastructures and dams even in low seismicity region has resulted an increase in the seismicity at present (induced seismicity) compared to the past. As a result of which, frequent earthquakes, microtremors can be evidenced in the seismically stable parts of the country.

Induced effects such as landslides, liquefaction and amplified ground shaking are the results of modified ground motions. This modification occurs due to the presence of local soil at that site. Damages evidenced during 1999 Chamoli EQ (earthquake) in Delhi, 2001 Bhuj EQ in Ahmedabad, 2005 Kashmir EQ and many more are clear indication that induced effects can be triggered even at far distance from the epicentre Also such effects are controlled by subsoil characteristics available at the site of interest which are known as local site effects. Site response analysis at the site of interest determines the change in ground motion characteristics between the bedrock and the ground surface due to the presence of subsoil layers having varying characteristics between the bedrock and the surface. Thus, these modified ground motions trigger induced effects. Proper estimation of induced effects depends upon the accuracy in the site response analysis. Most of the earlier site response studies were region specific where a broad picture of ground motion amplification, predominant period, period of highest spectral accelerations were estimated. Such studies can be used either as preliminary studies for site specific analyses or as guidelines in case a site specific study needs to be performed. Further, the results from such research studies are usually higher and their direct application for design purposes or estimation of the safety of site against induced effects is very limited.

Over the last decade, the scenario in the industry has changed drastically. Many a times now the client wants the designer to conduct project specific studies in the construction industry. Further, the outputs should be used for the foundation design purposes rather considering codal provisions or other earlier published studies alone. Such approaches are generally followed for highly important structures such as dams and Nuclear Power Plants but for other projects, limited to no such site specific studies are available. In this paper, quantification of local site effects based on drilled boreholes at typical site is attempted. Further, the results are compared with the codal provisions after suitable filtering based on various observations made during this work. The procedure followed here is developed in this work and will be very much helpful in arriving at more reliable values both from the client as well as designer point of view and can be followed in similar studies in the future.

2. STUDY AREA

Area considered in this work belongs to the shallow crustal region of India. The study area belongs to seismic zone IV as per [1]. Thus, even though the seismicity is moderate, understanding the local site effects of the region will be help to arrive at suitable design guidelines and other useful parameters. Since the boreholes are drilled for a client driven project and not under a research work, the location of the site has not been disclosed here. Past studies suggest repeated moderate to severe damages in the study area due to distance earthquakes either from the Himalayan seismic belt or due to regional earthquake from other nearby local sources.

3. SUBSOIL LITHOLOGY

In order to understand the subsoil lithology, 41 boreholes are drilled up to 30 m depth. All the boreholes are drilled with a diameter of 150 mm as per [2] with N-SPT values measured regularly at 1.5 m interval as per [3]. Disturbed and undisturbed samples are collected at possible depths as per [4]. N-SPT values and depth of sample collection are logged during the field testing. The physical properties are measured in the laboratory using disturbed soil samples as per [5] and used for soil classification in this paper. A typical borelog obtained from the field studies is shown in the Figure 1.

BH No B1	Ground Water Table at 0.9m below Ground Level (GL)						
Depth below GL(m)	Soil Description	Thickness of Layer	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					SPT	11	26
12.0	Medium 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					SPT	23	69
24.0	Medium 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					SPT	29	96
30.0	Medium 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

Fig. 1: Typical borelog from the study area considered in the present work

It can be observed from Figure 1 that surface layer consists of filled up soil of 1 m thickness. Deeper layers consist of alternate beds of silty sand (SM) and medium to low compressibility clays (CI-CL). These layers are available in thickness ranges from 1 m to 6 m till a depth of 30m below the ground level. Disturbed and undisturbed soil samples are collected during the borehole drilling at various depths as mentioned in Figure 1. Water table level is reported after observing for 24 hours to ascertain no further variation. As mentioned in Figure 1, the water table for this borehole is 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 suggested the presence of silty sand at most of the locations at various depths followed by layers of medium to low compressibility clays. Soil characterization as per NEHRP [6] classification system using N-SPT values suggests the presence of soft soil ($N < 15$) up to 4 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. National Earthquake Hazard Reduction Program (NEHRP; [6]) based soil classification based on 30m average N-SPT (N_{30}) suggest site class E ($N_{30} < 15$) and D ($15 < N_{30} < 50$) for all the boreholes.

4. SITE RESPONSE ANALYSIS

Massive damages due to earthquake can be evidenced not only in the epicentral regions but at far distance as well. Presence of soft soil in the near surface region causes a complete change in the ground motion characteristic. As a result surface scenario becomes more devastating and the same can be prolonged to far distances. Induced effects such as amplified ground motion, liquefaction and landslides are the consequences of modified ground motion as reached to the surface. Recent example of site effect leads to 2011 Sendai earthquake in Japan and 2011 Sikkim earthquake in India. 2011 Sendai earthquake (Mw=9.0), even though the epicentre was 130 km off from the eastern causes massive liquefaction and foundation failure due to differential settlement at Maihama and Tokai Mora which were located 150 km from the epicentre [7]. 2011 Sikkim earthquake (Mw=6.8) causes several building collapse in Mangam, Jorethang and lower Zongue located 150 km away from the epicentre. Ground motions due to 2011 Sikkim earthquake were felt at many places in west Bengal and Bihar as well [8]. Thus, irrespective of the magnitude of the earthquake, the damages can be spread in a wider area depending upon the subsoil properties.

In this work, the site response of a typical construction site is attempted to understand its response during future earthquakes and to take necessary remedial actions. The site is selected by the client for important structure related to public utility. Equivalent linear site response approach is considered in this work using SHAKE2000 [9].

4.1. Ground Motion Selection

Recorded ground motions in India are available only after 1986 and since then no major or great event has occurred in the Himalayan belt. Ground motion characteristics which controls the response of the soil during an earthquake are frequency content, duration and amplitude of the earthquake ground motion. In order to account for uncertainty about these ground motion characteristics during the future earthquake a large set of bedrock motions should be considered. These selected ground motions should cover a wider range of amplitude, frequency content and duration. In the absence of recorded data available covering a wide range of amplitude, globally recorded data at bedrock are considered in the present. All the data are taken from

PEER (Pacific Earthquake Engineering Research) database as given in SHAKE2000. Selected ground motions are not concentrated to any specific region but consists of ground motions from various parts of the globe. Since, all the ground motion characteristics are considered here, the region specific properties of the ground motion will not be remained significant. In total 30 ground motions, all recorded at bedrock level are considered in this work. The surface PGA to be determined from this work will be a function of the bedrock PGA and the local site effects. The bedrock PGA can be obtained from the seismic hazard analysis (SHA) for the study area conducted by earlier researchers. Further, the local site effects will be determined from the site response analyses to be performed in this work. The end results of the site response analyses to be used is the amplification factor [ratio of surface PGA (Peak Ground Acceleration) to the bedrock PGA] which is the normalized value with respect to the bedrock PGA. Thus, amplitude of selected ground motions will not affect the magnitude of surface PGA directly. Keeping this important factor in mind ground motions are selected. A wider range of amplitude (0.036g to 1.03g) are covered which may or may not be close to the bedrock PGA for the site as proposed by the seismic hazard study. Also the selected data covers a wide range of duration and frequency content. 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 1.2 Hz to a highest value of 50 Hz. Similarly, the duration of the selected ground motions are varying from a lowest value of 6.8 s to as high as 140 s as shown in Table 1. Hence, it can been seen from Table 1 that a large variation of ground motion characteristics have been considered to account for the future earthquakes for the region.

4.2. Dynamic Soil Properties

The stress-strain behaviour of soil is nonlinear. The modulus reduction (G/G_{max}) and damping of the soil is a function of the level of strain and is different for different soils. In equivalent linear approach, an initial value of shear modulus and damping is assumed. Using these shear modulus and damping models, one-dimensional site response analysis is carried out by updating level of ground shaking (Shear Strain) using an iterative process. Thus, the site response of a soil is a function of the modulus reduction (G/G_{max}) and damping properties of the soil. In general these modulus reduction (G/G_{max}) and damping ratio curves for each of the material need to be obtained from laboratory tests such as simple shear, torsional shear, cyclic triaxial and

Table 1: Ground Motion characteristics of the selected bedrock motions

PGA (g)	Predominant Frequency (Hz)	Duration (s)
0.013	25.00	40.00
0.027	3.13	15.98
0.033	4.55	34.07
0.036	10.00	18.59
0.046	3.85	10.25
0.046	16.67	39.95
0.049	7.14	38.96
0.055	8.33	39.95
0.056	8.33	39.95
0.07	5.00	40.00
0.075	12.50	6.80
0.08	16.67	10.01
0.086	4.17	75.35
0.088	2.50	51.80
0.09	1.22	60.23
0.098	8.33	24.58
0.1	5.56	19.89
0.116	25.00	26.09
0.12	16.67	79.39
0.13	3.13	22.00

0.14	2.27	81.06
0.197	5.56	24.00
0.215	10.00	40.00
0.22	5.00	139.97
0.24	5.00	39.59
0.25	12.50	40.91
0.27	1.92	40.00
0.31	16.67	39.94
0.53	2.50	42.00
1.03	50.00	59.98

resonant column tests [10,11]. However due to limited resources and the standard curves available for each type of material based on large number of tests. Such curves are being used in most of the site response studies [11]. These curves can be selected depending upon the soil type, it's over consolidation ratio (OCR), plasticity index (PI) and many other properties which are resemblance of that soil. In the present work, three types of soils are mainly encountered as given in Figure 1. These soils include silty sand, low compressibility clays and medium compressibility clays. Since the client recommendations are not to place foundation in the fill layer, this layer has not been modelled while performing site response analysis. Thus three types of soils are considered from the SHAKE database as 1) Average sand for silty sand; 2) Clay with PI 0 to 10 and 3) Clay with PI 10-20. G/G_{max} and damping curves for sandy soil given by [12] is used for silty sand layers. G/G_{max} and damping curves developed by [12] for sandy soil based on large number of different types of laboratory and field tests on sand from California region. Similarly, [13] studied G/G_{max} ratio of clay with different PI with over consolidation ratio (OCR) of 5 to 15. Authors [13] found that low value of PI has considerable effect on position of G/G_{max} curve when compared to high PI clays. Authors [13] proposed different G/G_{max} curve for clay with different plasticity Index (PI) values. Hence, G/G_{max} curve for clay soil is selected from [13] based on PI values.

The average damping curve for clay as per [12] is used for both the clays (CI and CL) since damping curve is independent of PI of the clays. Selected damping curves and the G/G_{max} for various soil types in this work are shown in Figure 2 and 3 respectively. Water table is considered at the same depth in the SHAKE2000 modelling as obtained from the borelog reports. Subsurface soil properties and soil dynamic model curves discussed above are used as inputs modelling of soil columns. Further, each of the soil column is subjected to all the selected ground motions and the response in terms of amplification factor are observed.

4.3. Analysis and Results

In order to perform equivalent linear analyses using SHAKE2000, all the 41 soil columns are generated using the soil properties obtained from the borelog. Three types of soils are considered while defining the dynamic soil properties as discussed earlier. *In-situ* densities and the thicknesses of various layers are modelled. Thicker layers (> 3m) are subdivided into 3 m thickness. N-SPT obtained from the *in-situ* test are used to determine the initial shear modulus of the soil. Once the soil column are modelled, the selected ground motions are applied at 30 m depth. Outputs in the form of

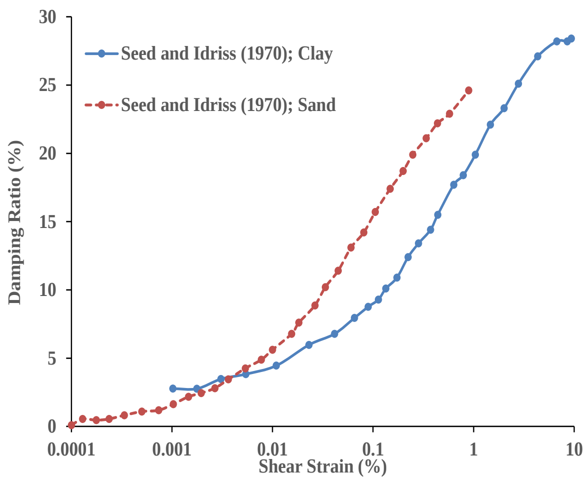

Figure 2: Damping ratio curves for different soil types

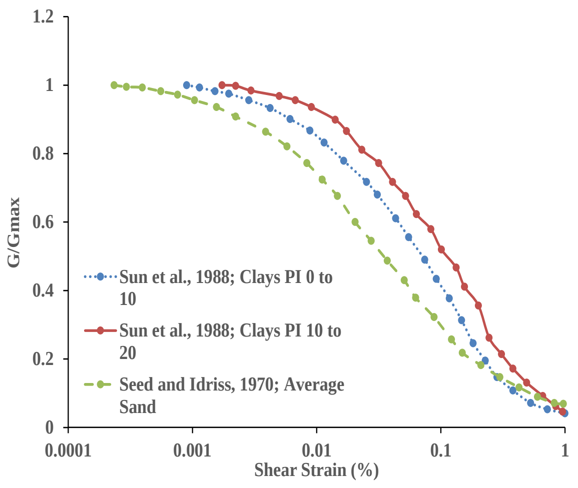

Figure 3: G/G_{max} curve for different soil types

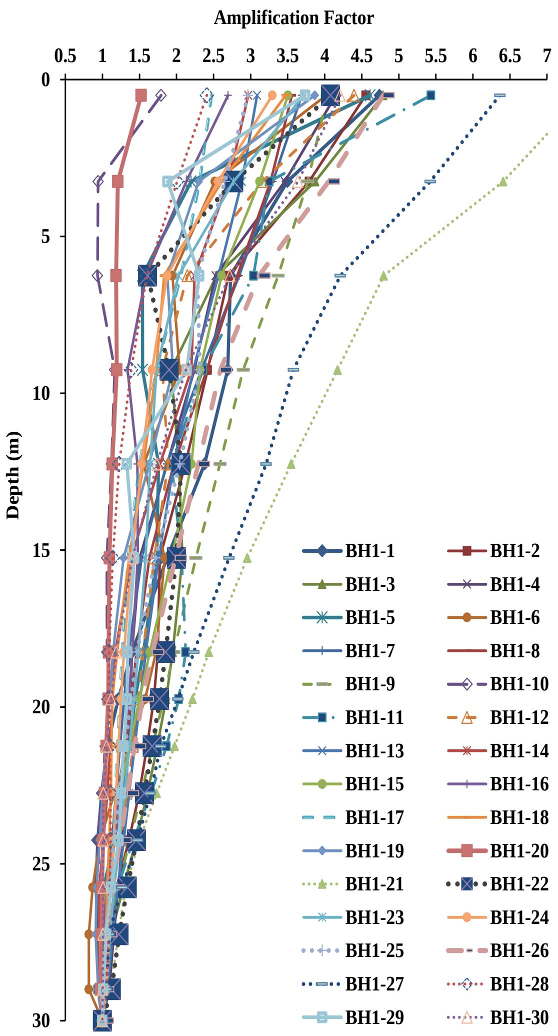

Figure 4: Typical plot showing the variation in amplification factor corresponding to selected ground motions

acceleration time history, stress-strain time histories at selected layers are obtained. Also, variation in PGA with respect to depth is also obtained in output. Further the surface PGA obtained from the output files are used for the determination of amplification factor. Figure 4 shows the variation of amplification factor considering various ground motions as bedrock motion. It has to be highlighted here that amplification factor variation shown in Figure are corresponding to borelog presented in Figure 1. Since PGA values at various depths are normalized with respect to the bedrock PGA, for this reason all the graphs are narrowed to amplification factor of 1.0 at 30 m depth. Variation in amplification factor with depth corresponding to various ground motions can be BH1 is presented in Figure 4 below. Numbers given in the legend are the nomenclature given to the ground motions selected. It can be observed from the Figure 4 that the amplification factor is almost constant between 25 m and 30 m depth. Above 25 m, certain ground motions shows large variation in amplification factor along the depth as shown in Figure 4. Ground Motion 20 and 10 having PGA of 0.53g and 1.03g are showing almost minimal to no amplification in the ground motion amplitude between the surface and the bedrock. Further, ground motion 21 and 27 having bedrock PGA of 0.028g and 0.013g respectively shows a large variation in amplification factor. The surface amplification factor obtained corresponding to ground motion 21 and 27 are 7.4 and 6.3 as can be seen from Figure 4. Similarly ground motion 2, 11, 13 and 15 having bedrock PGA of 0.027g, 0.033g, 0.055g and 0.036g respectively. The ground motions yield surface amplification factor of 4.55, 5.43, 3.1 and 3.5 respectively. Similarly ground motions having bedrock PGA of 0.25g, and 0.27g causes an amplification in bedrock motion by a factor of 2.9 and 3.6 respectively. Similar observations can be made from other borehole analyses as well. Based on these observations it can be concluded that higher values of amplification factors are corresponding to lower bedrock PGA values. Similarly, no or minimal amplification are observed in case the bedrock PGA is beyond 0.52 g. Further, medium range of amplification (3-5) in this work are obtained corresponding to PGA of 0.2-0.4g. A collective observation made considering all the borehole results also give similar findings in terms of bedrock PGA and surface values of amplification factor.

Above observations correlates the amplitude of bedrock motion upon surface amplification. In addition to this the effects of soil type and its shear strength properties upon amplification are also observed. Comparison of N-SPT against amplification factor obtained from all the boreholes suggests lower value of amplification in case of sandy soil with N-SPT ≥ 50 beyond 25 m depth. It has to be mentioned here that the values of N-SPT referred in this paper are the uncorrected values. Thus, no correction factor of any type is applied to the field measured values while making any qualitative observation. Similar to sandy soil, clays of low to medium compressibility as observed from Figure 1 and having N-SPT ≥70 at depths below 25 m shows no to minimal amplification. Again the N-SPT referred here are field recorded data without any correction factor. These observations are very important as such conclusions can be used while deciding the depth of borehole to be drilled in order to understand the local site effects. However, in addition to the N-SPT, the thickness of the layer having the above recommended N-SPT may also plays a vital role. However, this observation and other careful statements made here may be bound to the scope of this work. Thus more number of observations and analysis are needed in order to give some kind of guidelines for field testing. Site classification based on 30 m soil properties are usually practised. Further, the local site effects are also studies keeping in mind the subsurface lithotechnical details up to 30 m depth. Observations made from this work needs to be generalized based on more data. Future studies in this direction will be helpful to comment upon the depth of borehole to be considered for site characterization and to study the local site effects. It needs to be highlighted here that the study area considered in this is a part of shallow subsurface deposits. Commenting about similar guidelines for deeper deposits (> 100m) without the support of any deeper borehole based analyses may not be appropriate and is not the scope of this study. Further, such observation can be studied for the cost effectiveness as the ultimate depth of boring may get reduce in case dense soil (N-SPT > 50) is available at 25 m rather than present practise of drilling up to 30 m depth as a common guideline.

4.4. Surface PGA

Surface level of ground acceleration controls the building response during an earthquake. Thus, in case the ground shaking is too high, associated damages will be catastrophic. Further, the extent of damage is also a function of subsoil available. For this reason induced effects such as liquefaction, uneven settlements and landslides are evidenced in many of the earthquakes even at distant location. Thus, the source event for such induced effects may either be a regional earthquake or a distant event. In either of the case if the subsoil is soft/ low relative density, it will under large settlement and other induced effects.

In this work, as per the client’s requirement, surface PGA needs to be evaluated. Once the amplification factor is known, the surface PGA can be obtained from the product of amplification factor and the bedrock PGA. As mentioned earlier that the site under consideration comes under Seismic Zone IV. Limitations with the seismicity level presented in the IS code [1] for various regions of the country has been highlighted by many of the researchers. National Disaster Management Authority (NDMA), Government of India, developed the probabilistic seismic hazard maps for entire country. The entire country was divided into 7 tectonic zones based on the seismotectonic parameter characterization as per [14] considering 32 aerial sources. Ground motion prediction equations (GMPEs) for each of the tectonic regions were developed based on synthetic ground motion. Finite Fault models considering regional seismotectonic parameters were used to develop synthetic ground motion. The report based on the above detailed seismic hazard of the country as referred as [15] in this paper. Probabilistic seismic hazard maps for entire country are developed for different period for PGA [15]. In addition, spectral accelerations for various return periods were also developed by [15]. Overcoming the shortcoming of codal recommendations, bedrock PGA from [15] is considered in this work. Bedrock PGA for the site considering 10% probability of exceedence in 50 years as per [15] is 0.08g which is used in this work.

Based on the site response analysis, a wide variation in the amplification factor can be observed as given in Figure 4. Considering all the borehole analyses, the range of amplification factor variation is found from 1.0 to 7.4. Higher values of amplification factors such as 7.4 will yield surface PGA of 0.69g. This value is 2.9 times higher than the zonation factor of 0.24 for the study area as per [1]. This will have a direct impact on the construction cost/ ground improvement which may not be appreciated by the client. Hence, the range of amplification factor found from the above analyses needs to be reanalysed. Also it will enhance the confidence level of the geotechnical engineer. Keeping this in mind, three important observations are drawn from the analyses results as well as keeping in mind the design considerations. These are 1) in case the bedrock motion has very low PGA, the corresponding amplification factor is on higher side. However, the surface PGA values from for such ground motions are considerably low to cause significant level of ground shaking or any other induced effect. Thus, amplification factors corresponding to such ground motions are not realistic value should not be considered. 2) In case bedrock motion has PGA greater than 0.52 g, no considerable amplification between the bedrock and the surface are observed. This conclusion is drawn considering the analyses results from all the boreholes and using bedrock motions having PGA of 0.52 g and 1.03 g. Thus, bedrock motions having PGA greater than 0.52 g may not produce any influential result for site response study and should not be considered here. 3) From the designer's point of view any type of foundation suggested for this site will be in the soil with N-SPT ≥ 8. Close observations of the borelog suggested that the N-SPT ≥8 value has been encountered in the depth ranging 1.5 m to 2.5 m. This value of N-SPT is corrected for various correction factors and the Cyclic Resistance Ratio (CRR) is estimated. Using this value of CRR, the minimum value of Cyclic Stress Ratio (CSR) which can trigger liquefaction is calculated. This value of CSR is considering the value of factor of safety slightly close to unity. Thus, the surface level of PGA corresponding to CSR which can trigger liquefaction is determined. If the value of PGA obtained from site response are considerably less than PGA required to trigger liquefaction, the corresponding amplification factors can also be removed from the further analyses database. These three post site response analyses observations discussed here are original to this paper. These observations has not been discussed anywhere else. This procedure will be called as post filtering for site response analyses. The main aim to apply these observations is to narrow the range of amplification factor based on realistic demand at the site and also to optimize the construction cost. Once these three observations are applied to the total database, revised narrow band of amplification factor are observed. Figure 5 is corresponding to

Figure 2 after applying all the above three observations. It can be observed from Figure 5 that a wide range of amplification factor which was presented in Figure 2 has been narrowed. Earlier gotten values were between 1.0 and 7.4 which are now reduced down to a range of 1.8 to 4.1. The depth of fill observed for this borehole was 0.9 m and N-SPT ≥ 8 is observed at 4.0 m depth. For this reason, the variation in the amplification factor as presented in Figure 5 is starting from slightly deeper depth compared to Figure 4. The range of amplification factors presented here provides more realistic data compared to Figure 4.

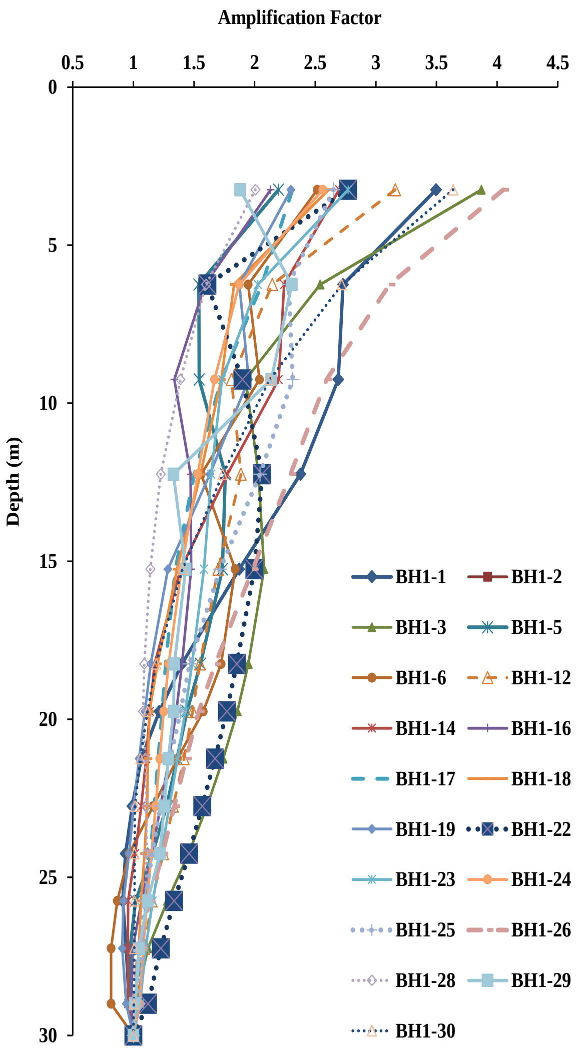

Figure 5: Revised amplification factor variation corresponding to Figure 1 after applying the three observations

These values can actually trigger liquefaction. Thus considering these values of amplification factor, the site if needed may be treated for ground improvement. Also, there will be considerable reduction in the construction cost as the demand is considerably less compared to the values obtained based on Figure4. This revised observations made in this are original to this paper and has not been recommended in earlier literature. Most of the site response studies report the value of amplification factor obtained directly from the analyses. Many times a very high values of amplification factors are recommended after such analyses which may not be of practical significance or a realistic one. In such case, a revised analysis considering the above post filtering procedure can bring down the range of amplification factor substantially.

Even though the range of revised amplification factor presented in Figure 5 are narrow compared to the values presented in Figure 4 but still it is a wide variation between 1.8 and 4.1. Hence, more refining of the outputs are needed in order to achieve at a single value. This value should be more realistic and should be a representation of local site effects along with the design and cost consideration. Keeping this in mind, the statistical analysis of the amplification factors obtained after the revised analysis is performed. This will enhance the confidence about the end result. Figure 6 presents the frequency distribution of revised amplification factors considering all the boreholes. Many of the analyses results discussed in support of Figure 4 are removed in Figure 6 during the post filtering. For this reason, the total number of observations mentioned on Y axis in Figure 6 are lesser. It can be observed in Figure 6 that the amplification factors are varying between 1.5 and 5.5. Further, the amplification versus frequency plot suggest an amplification factor of 2.5 corresponding to maximum frequency. Next higher frequency is corresponding to amplification factor of 3.5

with a considerable difference compared to 2.5. Higher values of amplification factor such as 4.5 are low in frequency. Further, the frequency reduces drastically when it reaches to 5.5. Similar to the observation made for 4.5 value, lower values of amplification factor such as 1.5 are also not frequent. Hence, only considering the impact on construction cost also, the lowest value of amplification factor cannot be recommended.

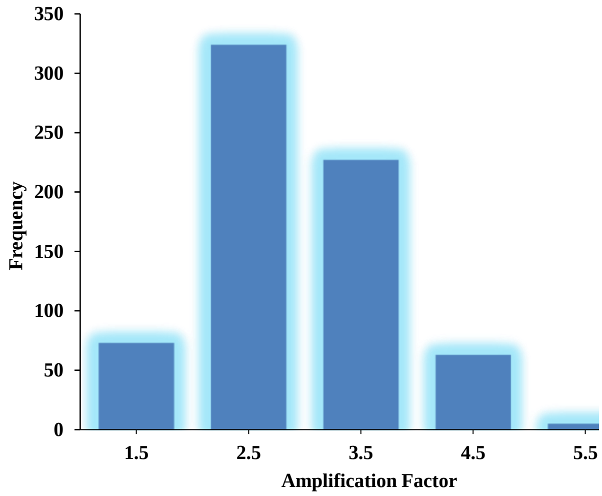

Figure 6: Plot of amplification factor versus frequency considering all the borehole analyses

Similarly, keeping the safety as the moderate criteria based on the utility, very highly values of amplification factor which are very rare as well, can be avoided. Considering the highest frequency amplification factor from Figure 6, a value of 2.5 is recommended from this work. Based on this value of amplification factor and the bedrock PGA of 0.08g as discussed earlier in this paper, a surface PGA of 0.20g has been recommended from this work. This value of surface PGA is slightly lesser with respect to zonation factor of 0.24g as per [1] for the study area. Thus at the end of the analysis, two recommendations are made. One is 0.20g which is found based on the current analysis and other value of 0.24 which is slightly higher than the present findings since it has been recommended by the standard. Construction cost may not vary considerably in selecting either of the two values. Further, the surface PGA and the borehole data can be used collectively to determine the safety of site against liquefaction. Also, the target values for ground improvement can be recommended in the future work. The impact of considering the water table either at the surface level or at the actual level upon the cost can also be studied further.

5. CONCLUSION

Site response is a very prominent area as it controls the damage scenario during an earthquake. The extent of damages not only a function of earthquake magnitude and its distance from the site but also the subsoil characteristics at the site. Large number of field tests both geotechnical and geophysical are available to determine the *in-situ* subsoil properties. The subsoil properties change drastically and thus planning for field testing for site characterization is a challenging task. In addition, the depth of borehole to be considered is another challenge which needs to be tackled. In the present work one typical site is given by the client for the construction of public utility. Large number of boreholes are drilled during the work up to 30 m depth. Based on the borelog, alternate layers of silty sand and low to medium compressibility clays are encountered. In most of the locations, fill is encountered in the surface layer. Considering the design consideration, fill is not considered in site response analysis. Bedrock motion to be used plays a vital role as the ground motion characteristics such as amplitude, duration and frequency content of the input motion controls the soil response. In absence of regional recorded data and also to account for uncertainty in ground motion characteristics due to future earthquake, 30 ground motions are considered from global earthquakes. All these ground motions are recorded at bedrock level and are taken from PEER database. Based on the soil type obtained from the borelog, suitable G/G_{max} and damping curves are considered. Each of the borelog is subjected to 30 ground motions and their response in terms of amplification factor are observed. Important conclusions made from analysis results show high amplification factor in case the input motion has low PGA values and no to minimal amplification in case of PGA ≥ 0.52g. Also, a close observation from all the boreholes suggest that below 25 m depth, site amplification will not be considerable in case; a) N-SPT ≥ 50 for sandy soil and N-SPT ≥ 70 in case of low to medium compressibility clays. This observation is new to thins work and will be very useful in terminating the depth of borehole at shallow depth in case sufficiently stiffer medium is available. Also, it will lead to considerable cost cutting on borehole drilling. Since the obtained results shows a wide variation in the amplification factor from 1.0 to 7.4, certain close observations are made considering the analyses results and the design guidelines for this work. Based on these observations, reanalyses of the results are attempted. As a consequence of which the amplification factors are narrowed to the range of 1.8 to 4.1. Further, this range has been reduced to a single value of 2.5 based on statistical analysis of the filtered database.

Large number of site response studies are available in the literature. Most of these studies yield a very high level of surface PGA or amplification factor in the range of 5 and above. Considering the practical situation in accepting such a high values will enhance the construction cost drastically and will be highly uneconomical. In a competitive world like today, cost cutting by careful observation is a demanding and challenging task. Further, it the targeted values should be realistic as it will enhance the confidence of the designer. In case the soil is found to undergo liquefaction, it needs to be treated. For such analysis again the surface PGA values are the controlling factor. Thus a slightly high value of surface PGA reported will enhance the ground improvement cost as well as the foundation construction cost. Above study provides a very useful guideline on the borehole termination in case of shallow deposits and how the site response results obtained from standard tools can be useful for geotechnical applications. This work is new in its own kind and provides clear guidelines for future works on similar ground. Application of reanalyses suggested in this work for deep soil sites need additional studies and are not covered here.

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