Effect of Shear Modulus Correlation on Site Response Study

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Abstract

Site response analysis requires dynamic/shear moduli of subsurface layers. A low strain shear modulus plays a fundamental role in the geotechnical earthquake engineering to estimate the hazard parameters for site response studies and seismic microzonation. Shear modulus is usually obtained from measured shear wave velocity and density or from standard penetration test (SPT) N values using correlation between SPT N and shear modulus. Many shear modulus correlations between N and shear modulus (G_{max}) are available in the literature but selected few correlations are repeatedly used to obtain site response parameters. Anbazhagan et al[2,3] presented a detailed review of the available fifteen G_{max} correlations with SPT N and a proposal of new correlation applicable to any region. The objective of this study is to identify the suitable G_{max} correlation for different soil types such as sand, clay and gravel or the mixture of all (sand, clay, gravel, sandy soil) considering recorded ground motion data with soil profile.

In this study, sites with earthquake data recorded at the surface, drilled soil profiles along with SPT N values and shear wave velocity are selected from K-NET (Japanese website) data base. Shear wave velocity is used to classify the sites. As bedrock recorded ground motion data is not available for the most of site with SPT N values, ground motion recorded in site class A and B is used as input to understand the response of site class C, D and E. Collected earthquake data consists of moment magnitude (MW) of 5.0 to 9.0 which are recorded at different epicentral distances. Surface ground motion and response spectrum are obtained by considering dynamic properties from 16 G_{max} correlations. The estimated values are compared with surface recorded data of the same event. The study shows that peak ground acceleration (PGA), amplification factor (AF) and average horizontal spectral amplification (AHSA) are obtained from very few G_{max} correlations comparable with recorded values. G_{max} relation giving values close to record data is considered as a suitable correlation for specific soil type.

Keywords: Amplification factor, Shear modulus, SPT N vs G_{max}, Peak ground acceleration, Response Spectra, Site response.

Introduction

Different sites located at a same epicentral distance may have different soil response during earthquake. Site amplification of seismic energy due to soil conditions and damage to built environment was demonstrated by many earthquakes during the last century to the greater extent. The destruction caused by the Guerrero earthquake (1985), Spitak earthquake (1988), Loma Prieta earthquake (1989), Kobe earthquake (1995), Kocaeli earthquake (1999) are important examples of site specific amplification of ground motion. Even at locations far away (100-300 km) from the epicentre this amplification can be significant[5]. The 2001 Gujarat-Bhuj earthquake in India is another example with notable damage at a distance of 250 km from the epicenter.[12,31] These failures resulted from the effect of soil condition on the ground motion that translates to higher amplitude; it also modifies the spectral content and duration of ground motion.

The nature and distribution of earthquake damage are strongly influenced by the response of soils to cyclic loading. Parameters that characterize the response studies are earthquake source, source nature and distance from the source, wave path, geological context, upper soil properties, topography and primary site effects.[1,10] These effects can be quantified by the site response analysis which involves the propagation of earthquake motions from the base rock to ground surface through overlying soil layers. This response is controlled in large part by the mechanical properties of the soil. Soil properties that influence wave propagation and other low-strain phenomena include stiffness, damping, Poisson’s ratio and density. Stiffness of soil deposits, represented by shear modulus, is an important property for evaluating the dynamic responses of soil structures at different sites.

Shear modulus is one of the important site parameters which affect site response studies along with the depth of the bedrock and the type of sand or clay[14]. Shear modulus is usually obtained from measured shear wave velocity and density or from standard penetration test (SPT) N values using correlation between SPT N and shear modulus (G). Soil stiffness in the form of SPT N value is a useful parameter and is widely used to estimate amplification of seismic waves. Many regression equations between SPT N and shear modulus were developed considering different soil types.[2,3] However, few shear modulus correlations were being routinely used for site response analysis because those were in built in SHAKE2000[30] software. Limitation of inbuilt shear modulus correlation in the SHAKE2000 was highlighted by Anbazhagan et al[2,3]. Of available 18 shear modulus correlations, correlation given by Seed et al[28] and Kramer[19] are not considered further due its limitation. In this study an attempt has been made to identify suitable Shear modulus (G_{max}) correlation for site response analysis of specific soil type considering K-NET (Japanese website) recorded earthquake surface record with soil profile and SPT N values.

The soil profiles with measured SPT N values used in the present study were downloaded from K-NET; obtained data are classified according to National Earthquake Hazards Reduction Program (NEHRP) classification. Strong motion data recorded at site class-A or B is used as an input motion to compute amplification at another site class through site response studies. Amplification from response studies is compared with the recorded amplified earthquake event in terms of peak ground acceleration (PGA), amplification factor (AF) and average horizontal spectral amplification (AHSA).

Shear modulus correlations

Several empirical correlations were developed between low strain dynamic properties of soil such as shear wave velocity and shear modulus with SPT- N values. Among these correlation shear wave velocity correlations are widely published and used. However, shear stiffness of the soil depends on soil density and shear wave velocity. So shear modulus correlations are more appropriate for soil stiffness estimation than shear wave velocity correlations. Anbazhagan et al[2,3] presented a detailed review of the available fifteen G_{max} correlations with SPT N and a proposal of new correlation applicable to any region after 21 years gap. The existing correlations were developed by Imai and Yoshimura[16], Ohba and Toriumi[21], Ohta et al[22], Ohsaki and Iwasaki[23], Hara et al[13], Imai and Tonouchi[17] and Anbazhagan and Sitharam[4]. Kramer[19] has modified correlation developed by Imai and Tonouchi[17] for sandy soil by replacing measured N values with energy corrected N values [N_{60}].

New correlation was developed by Anbazhagan et al[2,3] based on measured data from Ohta et al[22], Hara et al[13] and Anbazhagan and Sitharam[4]. Seed et al[28] presented the correlation based on their previous studies. Seed et al[29] have presented G_{max} correlation based on Ohta and Goto data. Correlations proposed by Seed et al[28], Seed et al[29] and Kramer[19] are inbuilt in SHAKE2000[30] and widely used to calculate the shear modulus using SPT N values during site response analysis. In this study compatible and reliable 16 correlations are selected for site response study. These SPT N versus G_{max} correlations are given in table 1.

Ground motion and soil profile data

The main objective of this study is to identify best correlation to estimate the shear modulus by SPT N values for site response of different soil type. Data required for the present study is the detailed soil profile along with surface and bedrock recorded ground motions. Even though large numbers of ground motion records are available worldwide for different earthquakes, very limited records have complete subsoil properties like SPT N, density, soil profiles and shear wave velocity values. Data provided by K-NET (Kyoshin network- www.K-net.bosai.go.jp) has complete earthquake records with subsoil properties below ground motion recording instrument.

In this study, earthquake records with station subsoil profiles and SPT N values are selected from the K - NET. These data were being widely used to understand several site response analysis aspects by many researchers. Arjun and Ashok Kumar[6,7] used Japanese ground motion (K-NET) data for development of neural network model to estimate the duration of strong ground motion and peak ground acceleration by considering average values of four geotechnical properties of the site (SPT N, primary and secondary wave velocity and density of soil) whose magnitude is more than 5.0, with a hypocentral distance of less than 50 km. Several studies explained about amplification and site effects using Japanese ground motion data. Most of these studies were carried out by estimating soil column stiffness considering shear wave velocity given in K-NET and not based on SPT N values.

Soil Profiles: Sites with earthquake data recorded at the surface, drilled soil profiles with SPT N values and shear wave velocity are selected from K-NET (www.K-net.bosai.go.jp) data base. The magnitude scale used in Kyoshin Net is M_{JMA} estimated by Japan Metrological Agency (JMA). In this case, a total of five profiles of sand, three profiles of clay, five profiles of gravel and eleven profiles of mixed soil type for different earthquakes with different magnitudes of Japan have been downloaded and used for this study. Summary of soil profile used for the analysis is given in table 2. A typical soil profile is presented in figure 1. Selected soil profiles are classified according to National Earthquake Hazards Reduction Program (NEHRP) classification system. Equivalent shear wave velocity (Vs) values for 30 m depths (Vs^{30}) are followed for site classification in the NEHRP recommendation (The Building Seismic Safety Council BSSC, 2001) and also International Building Code (IBC) classification.[11,15,18]

Vs^{30} has been calculated for selected sites, and sites are classified according to NEHRP and IBC classification. Site classification of each site as per NEHRP and more details about site classification can be found in Anbazhagan and Neaz[3]. Earthquake magnitude greater than 5.0 is selected because magnitude less than 5.0 may not have a major concern in many engineering studies. The magnitude selected range in this study varies from 5.0 to 9.0 (Table 2). All data have minimum one record at a hard rock site such a Site class B or A, which are not given in table 2. The sites selected for the analysis have amplification in ground motion when compared to input motion.

Selection of input motion: Strong motion data of acceleration 0.05 g is of primary interest for engineers. In present study acceleration[9] greater than or equal to 0.05 g is considered. Acceleration less than 0.05 g will have moderate perceived shaking and very light potential to damage the structure. Most surface recorded ground motion with soil profiles and SPT N values do not have ground motion recorded at bedrock, hence in this study it has been considered that ground motion data recorded at site A or B is free from amplification and used as an input motion for other sites. Though many earthquakes data are available in K-NET but the same earthquake record at site class-A or B is available for few magnitudes. These data were selected and used as an input motion for sites C, D, E and F where surface recorded ground motion is available. For the strong motion data obtained from online record, baseline correction was applied, multiplied by scale factor which is mentioned in the header file of recorded ground motion data file and converted into acceleration time history. Figure 2 shows typical spectra of ground motion for site class B (used as input motion) and surface recorded ground motion for the same earthquake for different sites considered in the analysis.

Site response study using SHAKE2000[30]

In the present study, one-dimensional ground response analysis of the equivalent linear model has been carried out using SHAKE 2000[30] software in which motion of the object can be given in any one layer in the system and motions can be computed in any other layer. SHAKE2000[30] software was specially modified for this study by the developer such that any standard form G_{max} relations given in table 1 can be used to estimate the shear modulus using SPT N values. It can be noted here that this special modification is not commercially available for other user. In equivalent linear approach, the non-linearity of the shear modulus and damping accounts for the use of equivalent linear soil properties using an iterative procedure to obtain values for modulus and damping compatible with the effective strains in each layer.

In this approach, first, a known time history of bedrock motion is represented as a Fourier series usually using the Fast Fourier Transform (FFT). Second, the Transfer Functions for the different layers are determined using the current properties of the soil profile. The transfer functions give the amplification factor in terms of frequency for a given profile. In the third step, the Fourier spectrum is multiplied by the soil profile transfer function to obtain an amplification spectrum transferred to the specified layer. Then, the acceleration time history is determined for that layer by the Inverse Fourier Transformation in step four. With the peak acceleration from the acceleration time history obtained and with the properties of the soil layer, the shear stress and strain time histories are determined in step five. In step six, new values of soil damping and shear modulus are obtained from the damping ratio and shear modulus degradation curves corresponding to the effective strain from the strain time history.

With these new soil properties, new transfer functions are obtained and the process is repeated until the difference between the old and new properties fits in a specified range. The basic approach of one dimensional site response study is the vertical propagation of shear waves through soil layers lying on an elastic layer of the rock which extends to infinite depth. The horizontal displacement due to the vertically propagating harmonic s-waves in each material is given by:

$$u_s(z_s,t) = A_s e^{i(\omega t + k_s^* z_s)} + B_s\, e^{i(\omega t - k_s^* z_s)}$$
$$u_r(z_r,t) = A_r e^{i(\omega t + k_r^* z_s)} + B_s\, e^{i(\omega t - k_r^{''} z_s)}$$

In the equations subscripts *s* and *r* refers to soil and rock respectively; *u* is the displacement, ω is the circular frequency of the harmonic wave and *k** is the complex wave number.

No shear stress can exist at the ground surface ($z_s=0$), so

$$\tau(0,t) = G_s^* \gamma(0,t) = G_s^* \frac{\partial u_s(0,t)}{\partial z_s} = 0$$

where $G_s^* = G(1-2i\beta)$ is the shear modulus of the soil. In this study shear modulus of each layer is estimated considering SPT N values of layer and 16 shear modulus correlations are given in table 1. The soil surface amplitude can be obtained as the product of the rock outcrop amplitude and the transfer function which is defined as the ratio of the soil surface amplitude to the rock outcrop amplitude. Therefore, the response of the soil layer to a periodic input motion can be obtained by the following steps:

Schnabel et al[25] explained that within a given layer (layer *j*), the horizontal displacements for the two motions (motions A and B) may be given as:

$$u_r(z_j,t) = \left(A_j e^{ik_j^* z_j} + B_j e^{-ik_j^* z_j}\right) e^{i\omega t}$$

Thus, at the boundary between layer *J* and layer *J+1*, compatibility of displacements requires that

$$A_{j+1} + B_{j+1} = A_j e^{ik_j^{''} z_j} + B_j e^{-ik_j^{''} z_j}$$

Continuity of shear stresses requires:

$$A_{j+1} + B_{j+1} = \frac{G_j^* K_j^*}{G_{j+1}^* K_{j+1}^*}\left(A_j e^{ik_j^{"} z_j} + B_j e^{-ik_j^{"} z_j}\right)$$

The effective shear stress of equivalent linear analysis is calculated as:

$$\gamma_{eff} = R_\gamma \gamma_{\max}$$

where $\gamma_{\max}$ is the maximum shear strain in the layer and R_γ is a strain reduction factor often taken as:

$$R_\gamma = \frac{M-1}{10}$$

where *M* is the magnitude of the earthquake.

Soil behaviour under irregular cyclic loading is modeled using modulus reduction (G/G $_{max}$) and damping ratio (β) vs. strain curves. The non-linearity of the shear modulus and damping is accounted for by the use of equivalent linear soil properties using an iterative procedure to obtain values for modulus and damping compatible with the effective strains in each layer as discussed above. The degradation curves of sand, clay and rock used in the present work are those proposed by Seed and Idriss[27], Vucetic and Dorby[32] and Schnabel[26] respectively. Here only the shear modulus for each layer is changed to get a response at surface for each G_{max} relation and the remaining parameters are kept constant. Surface response parameters for each site from 16 G_{max} relations are compiled and compared with recorded surface parameters. Estimated PGA, amplification factor and average horizontal spectral amplification (AHSA) are in the period range of 0.4-2.0 sec using each G_{max} to compare with recorded values in each site.

Results and Discussion

Equivalent linear (EQL) analyses are the most common approach used to perform one dimensional site response analysis. As a result of response studies peak ground acceleration (PGA) with depth, response spectra for each layer of soil and Fourier spectrum are arrived. These are further used to estimate PGA, amplification factor and AHSA for each site considering 16 G_{max} correlations which are compared with recorded surface motion at each site. Typical plot of PGA variation obtained from 16 G_{max} correlations for sand, clay, gravel and mixed soil sites are shown in figures 3 to 6. PGA obtained from site response analysis on 16 G_{max} correlations is compared with recorded PGA at the surface for each site.

Amplification factor has been estimated considering the input and surface estimated peak ground acceleration values and compared with amplification values from the recorded surface motion. Typical amplification values from 16 G_{max} correlations and recorded data are given in figure 7 to 10 for sand, clay, gravel and mixed soil sites. Typical recorded site surface response spectrum and estimated spectra considering 16 G_{max} correlations are given in figures 11. Average horizontal spectral amplification proposed by Borcherdt et al[8] for the period range 0.4-2.0 s has been calculated for all the response spectrum plots obtained from the equivalent linear analysis and compared with recorded AHSA values. G_{max} correlation gives estimated values of PGA, amplification factor and AHSA close recorded values are considered as a suitable correlation for a particular type of soil to estimate response parameters.

Peak Ground Acceleration: Surface PGA values are widely used to represent amplification and site effects of the sites. In this study, surface PGA of each site for dynamic property values estimated from 16 G_{max} correlations is compared with recorded PGA values. A typical comparison of surface PGA values from 16 G_{max} correlations is shown in figures 3 to 6. It can be noted from figures that the predicted PGA value is more than the recorded value. But comparatively very few correlations predict PGA close to recorded values. PGA obtained from different correlations are compared with recorded PGA under five groups of percentage error varying from ±0 to ±50% with interval of ±10% error. Among 16 G_{max} correlations, correlations which predicts close to recorded values with the lowest percentage of error are summarized in table 3.

Site EHM006 (sand overlying rock), for EQL analysis correlations 12, 13, 16 and 10 predict error of >±50% (Table 3). For profile MYG002 which is up to a shallow depth of sand (4 m), for a magnitude 6.8, correlation 8, 4 and 12 predict well within error of ±30-40% (Figure 3). For same profile with magnitude 5.1, correlation 4 and 8 predict well with error of >±50%. Correlation 12, 8 and 4 predict good within the error of ±30-40%, for the same profile with magnitude 6.4. For magnitude 7.0, correlation 8, 4, and 14 predicts lower percentage error (±0-10%) with recorded PGA and for the other two magnitudes (7.2 and 9.0) of the same profile MYG002, the correlation 4, 8 and 12 predicts good with error percentage of ±10-20%.

For the profile MYG003 which is upto a shallow depth of sand, for a magnitude 7.0, correlation 2, 11, 4 and 14 predict error of ±20-30%. But all the equations predict error of ±0-10% for the same profile with magnitude 6.4. For the same profile (MYG003) with magnitude 7.2 and 9.0, correlation 8, 4, 11 and 12 predict good within the error bar of ±10-20%. All correlations predict lower amplification through EQL analysis than the recorded PGA value for sand profiles, MIE008 and HRS019 which are up to depth of 20 m. The filled soil profile MIE008 with magnitude 7.4, where the soil fill around 13.5 m is overlaying the rock, correlation 5, 2 and 11 predict error of ±30-40% in the recorded value of EQL analysis of SHAKE. For site HRS019, correlation 12, 11 and 5 predict lower percentage of error compared to other correlations (Table 3).

The study of all sand profile results shows that correlation proposed by Ohasaki and Iwasaki[23] i.e. eq. no. 8 in table 1 gives surface PGA close to the recorded surface PGA for several sites and different magnitudes.

Clay soil profile FKS008 has 3 m of filled up soil followed by 5 m of clay above the rock, correlation 12, 11, 2 and 5 predicts lower percentage of error compared to other correlations for a magnitude 5.3. For the same profile with magnitudes 5.4 and 7.2, correlation 5, 2 and 11 predicts good with error of >±50%. Correlation 12, 15 and 13 predicts good for the same profile with magnitude 6.5 (Table 3 and Figure 4). Correlation 12 and 11 predict lower percentage of error (±10-20%) for the same profile with magnitude 9.0, considered to any other magnitude for the same profile. For the site HRS005, where the depth of the clay is around 8.0 m, correlation 8, 2 and 11 predict well. Other profile IWT017, where the depth of the clay is around 8.0 m above the rock, for a magnitude 6.8, correlation 5, 2 and 11 predict error of >±50%. For the same profile with other two magnitudes 7.2 and 9.0, same correlation (2, 11 and 5) predicts better than the other correlation. It has been noticed from the results that correlation given by Obha and Toriumi[21] i.e. eq. no. 2 in table 1, predicts surface PGA close to the recorded PGA for a wide range of magnitudes.

The site EHM002 has gravel up to a depth of 3 m which is followed by rock, correlation 10 and 4 predicts good. Site IWT023 has 5 m depth of gravel overlying above the rock, correlation 10, 15 and 13 predicts lower percentage of error with the recorded PGA (Table 3). Another two sites are NAR004 and NAR008 where gravel has fill soil above it. For site NAR004, correlation 12, 15, 13 and 10 predict better matching with recorded PGA for error of >±50%. For the site NAR008 with magnitude 5.5 (Figure 5), correlation 11, 2 and 5 predict lower percentage of error (±30-40%) than other correlations for EQL analyses. For the same profile with magnitude 6.9, correlation 2, 5 and 10 predict well than other correlations with error of >±50%. A site where gravel is up to a depth of 20 m (IWT007), for magnitudes 7.0 and 6.4, correlation 12, 15 and 13 predict error of ±10-20%.

Similarly for the same profile with magnitude 7.2, correlation 10 and 2 predicts better matching with error of ±20-30%. Finally, for the same profile with magnitude 9.0, correlation 10 and 2 predicts lower percentage of error of ±0-10% with recorded PGA. This study shows that correlations 10 in table 1 proposed by Imai and Tonouchi[17] predicts surface PGA values close to recorded values. It can be also noted that this correlation was given for the Alluvial Clay type of material. In mixed soil type of site MIE010, with a clay layer in between sand and filled up soil on top, for magnitudes 7.4 and 6.9, correlation 11 and 2 predict better matching with recorded PGA. For site FKS007 where gravelly soil with sand and fill soil at its top, correlation 15 predicts error of ±30-40% for magnitude 5.3. For the same profile with magnitude 9.0, except correlation 13 and 14, all other correlation matches well with error of ±10-20% with recorded PGA.

For site IWT004 with gravely soil and sand, correlation 15 predicts better with error of ±10-20%. For site IWT009 with gravel, gravely soil and fill soil, for a magnitude 6.8, correlation 11, 2, 12 and 5 predict lower percentage of error of ±0-10% than other correlation (Figure 6). For the same profile with magnitude 6.1, correlation 5, 12 and 2 predict better matching with recorded PGA for error of ±30-40%. Finally, for the same profile (IWT009) with magnitudes 6.4, 7.2 and 9.0, correlation 2, 11 and 15 matches better than other correlations with different percentage of error (Table 3). Correlation 5, 15, 2 and 11 matches better with recorded PGA for site EHM012, with gravel, gravelly soil and fill soil above the rock.

Profile MIE011 which is a mixture of clay, peat, and gravel with filled up soil at the top predicts higher amplification than any other soil mixtures, even though correlation 5, 11, 15 and 2 predict good with recorded PGA with error of >±50%. For site EHM009, with clay in-between gravely soil with fill soil on top, except correlation 2 and 15 all other correlations match well with recorded PGA for error of ±10-20%. Profile IWT001 with clay in between sand upto a depth of 1 m, for a magnitude 6.8, correlation 2 and 11 matches better with error of ±30-40%. Correlation 15 and 5 matches better than other correlations for the same profile with magnitude 7.2. Profile EHM003 which is a mixture of clay, sand and gravel, EQL analyses predicts almost matching with recorded PGA for all correlations except 15 and 5 for error ±10-20%. Site EHM010, which is a mixture of gravel and gravely soil, correlation 11, 2 and 10 predict lower percentage error of ±10-20%. For site WKY005, this consists of clay layer in between gravely soil; correlation 12 and 16 predict error of ±0-10% compared to other correlations for magnitude 5.4. Finally, for the same profile with magnitude 6.9, correlation 5 and 10 predicts well. Overall, correlation given by Imai and Tonouchi[17] i.e. eq. no. 11 in table 1 is predicting surface PGA close to record PGA for sites having an alternate layer of different soil types.

Amplification Factor: The amplification factor is calculated using a peak horizontal acceleration (PHA) at surface obtained from response study divided by PHA at rock level. The variation of AF with a recorded value for the typical sand profile is shown in figure 7. For site MYG002 with magnitude 6.8, the correlations 8 and 4 predict lower AF for EQL analysis than other correlations with error bar of ±30-40% (Figure 7). For same sites with magnitude 5.1, correlation 4 and 8 predict lower AF than other correlations with error of ±>50. For the same profile with magnitudes 6.4, 7.0, 7.2 and 9.0, correlation 8, 4 and 12 predict lower percentage error when compared to other correlations (Table 3). Correlation 12, 13, 10 and 15 predict lower AF for the site EHM006 with error of ±>50. For site

MYG003 with magnitude 7.0, correlation 2, 11, 4 and 14 predict lower AF error. All equations predict lower error of ±0-10% for the same site with magnitude 6.4. For magnitude 7.2, correlation 2 and 11 predicts better matching for response studies.

Similarly for same profile with magnitude 9.0, for EQL analysis all the correlations predict good with error of ±10-20%. For site MIE008, a correlation which predicts lower AF was 2, 5 and 11. Correlation 12, 11 and 5 predict lower AF for site HRS019 with error of ±>50. Correlation given by Ohasaki and Iwasaki[23] i.e. eq. no. 8 in table 1 is predicting amplification similar to recorded values for all range of magnitudes.

The variations of the amplification factor for clay soil type were more compared to other soil types considered in this study. For site FKS008 with magnitude 5.3, correlation 12, 11, 2 and 5 predict lower AF with error of ±>50. Correlation 5, 2 and 11 matches better than other correlation for the same site with a magnitude of 5.4 with the same percentage of error (±>50). For same profile with magnitude 6.5, correlation 12, 15 and 13 predict better with error of ±>50 (Figure 8). Other two magnitudes (7.2 and 9.0) and correlations 2, 11 and 5 predict well with different percentage of error (Table 3). Site HRS005 has higher AF than the other sites and of these correlations 8, 2 and 11 predict close to recorded values. For site IWT017 with magnitude 6.8, correlation 2, 5 and 11 predict lower AF with error of ±>50. Correlation 11, 2 and 5 predict lower AF than other correlations with error of ±>50 for the same site (IWT017) for the magnitude 7.2 and 9.0. It is observed that similar to PGA values, AF predicted by Obha and Toriumi[21] correlation closely matches with recorded AF values for most of Clay soil profile analysis.

For site EHM002 the correlation 10 predicts lower AF than other correlations. Correlation 10, 16, 15 and 13 predicts lower AF for the site response analyses of a site IWT023 with magnitude 6.8. For site NAR004 with magnitude 7.4, correlation 15, 13, 12 and 10 predict lower AF. For site NAR008 with magnitude 5.5, correlation 11, 2 and 5 predicts well with error of ±30-40% (Figure 9). For the same profile with magnitude 6.9, correlation 2, 5 and 10 predict better with error of ±>50. For site IWT007 with magnitude 7.0, correlation 12, 15 and 10 predict lower AF. Correlations 12, 15 and 13 predict better matching of AF than other correlations for the same profile with magnitude 6.4. Finally, for the same profile with other two magnitudes 7.2 and 9.0, correlation 10 and 2 predict better matching with less percentage of error for both EQL analyses (Table 3). Correlation given by Imai and Tonouchi[17] i.e. eq. no. 10, predicts better matching of AF than other correlations.

The mixed soil type site predicts better matching of AF when compared to other soil types (sand, clay and gravel). For site MIE010 with magnitudes 7.4 and 6.9, correlation 2 and 11 predict better matching of AF with error of ±10-20% for magnitude 7.4 and ±>50 for magnitude 6.9. For site FKS007 with magnitude 5.3, correlation 15 predicts better. For same profile with magnitude 9.0, except correlation 13 and 14 all other correlations predict lower percentage error for EQL analysis of SHAKE. Correlation 15 predicts better for the site IWT004 with magnitude 6.8 for error of ±10-20%. For site IWT009 with magnitude 6.8, correlations 11, 2, 15, 12 and 5 predict lower percentage of error of ±10-20% than other correlations (Figure 10). Similarly for the same profile with magnitude 6.1, correlation 5, 12 and 2 predict better. Correlation 2, 11 and 15 predict better matching of AF for the same site with magnitude 6.4 with error of ±20-30%. Finally, for the same profile (IWT009) with magnitudes 7.2 and 9.0, correlation 2, 11 and 5 predict good with error of ±0-10%. Correlation 5, 15, 11 and 2 predict lower amplification for site EHM012. For site MIE011, correlation 5, 11, 15 and 2 predicts good with error of ±>50.

For site EHM009 except correlations 2, 15 and 11, all other correlations predict lower amplification with error of ±10-20%. For site IWT001 with magnitude 6.8, correlation 2 and 11 predict better. Correlation 15 and 5 predicts well for the same site with magnitude 7.2 with error of ±>50. For site EHM003, except correlation 15 and 5 all other correlations predict good with error of ±10-20%. Correlation 11, 2 and 10 predict error of ±10-20% for the site EHM010 with magnitude 6.4. Finally, for the site WKY005 with magnitude 5.4, correlation 12 and 16 predict good with error of ±0-10%. For the same profile with magnitude 6.9, correlation 5, 6 and 10 predict good. The study shows that amplification from site response study of different correlations matches with amplification recorded at the surface with a certain percentage of error for equivalent linear analysis.

Response Spectrum: Response spectrum (RS) at the top layer of each site has been arrived considering 16 G_{max} correlations. Figure 11 shows a typical comparison of response spectrum from 16 G_{max} correlations and the recorded RS. The average horizontal spectral values of recorded data RS and estimated G_{max} correlations RS have been estimated for the period range of 0.4-2.0 as per Borcherdt et al[8]. Comparison of AHSA shows that correlation proposed by Ohasaki and Iwasaki[23] (Eq. no. 8) predicts close to recorded AHSA values for sand. Correlation given by Obha and Toriumi[21] (Eq. no. 2) predicts better for the clay soil column. Correlation given by Imai and Tonouchi[17] (Eq. no. 10) for clay soil predicts better for gravel soil column. Correlation given by Imai and Tonouchi[17] (Eq. no. 11) for alluvial sand predicts better AHSA values for mixed soil column i.e. sand, clay and gravel layers above the rock. These results are comparable with PGA and AF comparisons. It can be noted here that the SHAKE equivalent linear analysis gives PGA and AF values more than recorded values. Exact matching is not possible due to non availability of bedrock recorded ground motions. These results may be also verified with nonlinear analysis of the same profiles.

Summary and Conclusion

The several correlations between SPT N and G_{max} were developed for different soil with certain assumptions. Among these, two G_{max} correlations are being widely used for site response analysis which is not directly obtained from measured data. The main aim of this study is to summarize available G_{max} correlations for different soil type and identify best suitable G_{max} correlation for site response study of specific soil type. SPT N values in surface recorded earthquake data were compiled from K-NET data base for this study. Special options were created to estimate the shear modulus using different G_{max} correlations.

Site response analysis has been carried out by considering earthquake data recorded at a rock site as an input ground motion for soil profiles published in K-NET site. Surface ground motion and response spectrum are obtained from different G_{max} correlations. The obtained results are compared with surface recorded earthquake same event. The study shows that peak ground acceleration (PGA), average spectra (AS) and amplification factor (AF) obtained from very few G_{max} correlations are comparable with recorded PGA, average spectra and amplification factor.

This study shows that sand and a mixture of sand with sandy soil for different site classes and overburden thickness correlations 8 proposed by Ohasaki and Iwasaki[23] predict better than other correlations. Though all correlations predict the higher percentage of error for clay, correlation 2 proposed by authors Obha and Toriumi[21] predicts lower percentage of error than the other correlations and also better matching of average spectra. For the profile with gravel, correlations 10 proposed by Imai and Tonouchi[17] predicts less percentage error and better matching of average spectra than other correlation.

Table 1
List of G_{max} correlations used in the present study

S. N.	Correlations from different authors selected from the literature	Correlations in SI unit (MPa)	Remarks
1	Imai and Yoshimura (1970)	$G = 9.81N^{0.78}$	Mixed soil type
2	Obha and Toriumi (1970)	$G = 11.96N^{0.62}$	Alluvial sand, clay
3	Ohta et al. (1972)	$G = 13.63N^{0.72}$	Tertiary soil, Diluvial sandy and Cohesive soil.
4	Ohsaki and Iwasaki (1973)	$G = 11.94N^{0.78}$	All soil types
5	Ohsaki and Iwasaki (1973)	$G = 6.374N^{0.94}$	Sandy soil
6	Ohsaki and Iwasaki (1973)	$G = 11.59N^{0.76}$	Intermediate soil
7	Ohsaki and Iwasaki (1973)	$G = 13.73N^{0.71}$	Cohesive soil
8	Ohsaki and Iwasaki (1973)	$G = 11.77N^{0.8}$	All soil type
9	Hara et al. (1974)	$G = 15.49N^{0.668}$	Alluvial, Diluvial and Tertiary deposit
10	Imai and Tonouchi (1982)	$G = 17.26N^{0.607}$	Alluvial clay
11	Imai and Tonouchi (1982)	$G = 12.26N^{0.611}$	Alluvial sand
12	Imai and Tonouchi (1982)	$G = 24.61N^{0.555}$	Diluvial clay
13	Imai and Tonouchi (1982)	$G = 17.36N^{0.631}$	Diluvial sand
14	Imai and Tonouchi (1982)	$G = 14.12N^{0.68}$	All soil types
15	Anbazhagan and Sitharam (2010)	$G = 24.28N^{0.55}$	Silty sand with less percentage of clay
16	Anbazhagan et al., (2012)	$G = 16.4N^{0.65}$	All soil type

Table 2
Details of soil profile used for the analysis

Soil Type	Station	Site Class	Vs^{30}	Earthquake Magnitude (M_w)	Depth of Input motion (m)	PGA (g)
SAND	EHM006	C	531	6.4	10.00	0.34
	HRS019	E	175	6.4	20.45	0.43
	MIE008	D	287	7.4	15.45	0.16
	MYG002	C	469	6.8,5.1,6.4,7.0,7.2, 9.0	10.00	0.48,0.29,0.36,0.87,0.51, 0.67
	MYG003	C	476	7.0,6.4,7.2,9.0	10.00	0.56,0.19,0.41,0.79
CLAY	FKS008	D	304	5.3,5.4,6.5,7.2,9.0	10.00	0.12,0.12,0.14,0.15,1.03
	HRS005	C	440	6.4	12.44	0.29
	IWT017	C	437	6.8,7.2,9.0	10.15	0.29,0.12,0.33
GRAVEL	EHM002	C	501	6.4	10.00	0.21
	IWT007	D	358	7.0,6.4,7.2,9.0	20.00	1.05,0.26,0.25,0.71
	IWT023	C	490	6.8	10.00	0.33
	NAR004	C	395	7.4	10.50	0.16
	NAR008	C	487	5.5,6.9	10.50	0.39,0.12
MIXED	EHM003	D	237	6.4	17.30	0.46
	EHM009	C	363	6.4	11.15	0.28
	EHM010	D	349	6.4	16.40	0.20
	EHM012	C	503	6.4	10.00	0.19
	FKS007	C	510	5.3,9.0	10.25	0.16,0.70
	IWT001	D	239	6.8,7.2	10.00	0.84,0.07
	IWT004	D	337	6.8	10.00	0.28
	IWT009	C	580	6.8,6.1,6.4,7.2,9.0	10.00	0.48,0.17,0.27,0.29,0.58
	MIE010	D	242	7.4,6.9	20.44	0.15,0.08
	MIE011	C	692	7.4	10.00	0.14
	WKY005	D	338	5.4,6.9	10.00	0.59,0.15

For a mixture of clay and sand soil column correlation 11, proposed by Imai and Tonouchi[17] predicts better for different overburden thickness. The profile with clay in between gravely soils, correlation 5 proposed by Ohasaki and Iwasaki[23] predicts better. The profiles with a mixture of gravel, sand and fill soil at the top, correlation 15 proposed by Anbazhagan and Sitharam[4] predicts lesser percentage of error than other correlations. Even though several G_{max} correlations were available in the literature for different soil type, all of them may not be directly applicable to predict better site response parameters. Correlations suggested here are based on the selected profiles and analysis carried using EQL model. These findings may be further verified by carrying out non linear site response analysis.

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2. The authors wish to thank the Kyoshin Net Strong Motion Network of Japan for providing with an excellent earthquake database and valuable feedback for conducting this research.

Table 3
Comparison of PGA and AF obtained from different correlation with recorded value

Soil type		M_w	EQL analysis by SHAKE			
			PGA		AF	
			Eq. compared	Percentage difference	Eq. compared	Percentage difference
Sand	MYG002	6.8	8,4,12	±30-40%	8,4	±30-40%
		5.1	4,8	> ±50%	4,8	> ±50%
		6.4	12,8,4	±30-40%	12,8,4	±40-50%
		7.0	8,4,14	±0-10%	8,4	±10-20%
		7.2	4,8,12	±0-10%	4,8,12	±10-20%
		9.0	8,4	±10-20%	8,4	±10-20%
	EHM006	6.4	12,13,16,10	> ±50%	12,13,10,15	> ±50%
	MYG003	7.0	2,11,4,14	±20-30%	2,11,4,14	±20-30%
		6.4	All eq.	±0-10%	All eq.	±0-10%
		7.2	11,2	±0-10%	2,11	±0-10%
		9.0	8,4,12	±10-20%	All eq.	±10-20%
	MIE008	7.4	5,2,11	±30-40%	5,2,11	±30-40%
	HRS019	6.4	12,11,5	> ±50%	12,11,5	> ±50%
Clay	FKS008	5.3	12,11,2,5	> ±50%	12,11,2,5	> ±50%
		5.4	5,2,11	> ±50%	5,2,11	> ±50%
		6.5	12,15,13	> ±50%	12,15,13	> ±50%
		7.2	5,11,2	> ±50%	5,11,2	> ±50%
		9.0	12,11	±10-20%	2,11	±10-20%
	HRS005	6.4	8,2,11	> ±50%	8,2,11	> ±50%
	IWT017	6.8	5,2,11	> ±50%	5,2,11	> ±50%
		7.2	11,2	> ±50%	11,2	> ±50%
		9.0	5,2,11	> ±50%	5,2,11	> ±50%
Gravel	EHM002	6.4	10,4	> ±50%	10	> ±50%
	IWT023	6.8	10,15,13	> ±50%	10,16,15,13	> ±50%
	NAR004	7.4	12,15,13,10	> ±50%	15,13,12,10	> ±50%
	NAR008	5.5	11,2,5	±30-40%	11,2,5	±30-40%
		6.9	2,5,10	> ±50%	2,5,10	> ±50%
	IWT007	7.0	12,15	±10-20%	12,15,10	±20-30%
		6.4	12,15,13	±10-20%	12,15,13	±10-20%
		7.2	10,2	±20-30%	10,2	±10-20%
		9.0	10,2	±0-10%	10,2	±0-10%
Mixed Soil	MIE010	7.4	11,2	±10-20%	11,2	±10-20%
		6.9	2,11	> ±50%	2,11	> ±50%
	FKS007	5.3	15	±30-40%	15	±30-40%
		9.0	Except 13,14	±10-20%	Except 13,14	±10-20%
	IWT004	6.8	15	±10-20%	15	±10-20%
	IWT009	6.8	11,2,15,12,5	±0-10%	11,2,15,12,5	±10-20%
		6.1	5,12,2	±30-40%	5,12,2	±30-40%
		6.4	2,11,15	±20-30%	2,11,15	±20-30%

		7.2	2,11,15	±0-10%	2,11,5	±0-10%
		9.0	2,11,15	±0-10%	2,11	±0-10%
	EHM012	6.4	5,15,2,11	> ±50%	5,15,11,2	> ±50%
	MIE011	7.4	5,11,15,2	> ±50%	5,11,15,2	> ±50%
	EHM009	6.4	Except 2,15	±10-20%	Except 2,15,11	±10-20%
	IWT001	6.8	2,11	±30-40%	2,11	±30-40%
		7.2	15,5	> ±50%	15,5	> ±50%
	EHM003	6.4	Except 15,5	±10-20%	Except 15,5	±10-20%
	EHM010	6.4	11,2,10	±10-20%	11,2,10	±10-20%
	WKY005	5.4	12,16	±0-10%	12,16	±0-10%
		6.9	5,10	> ±50%	5,6,10	> ±50%

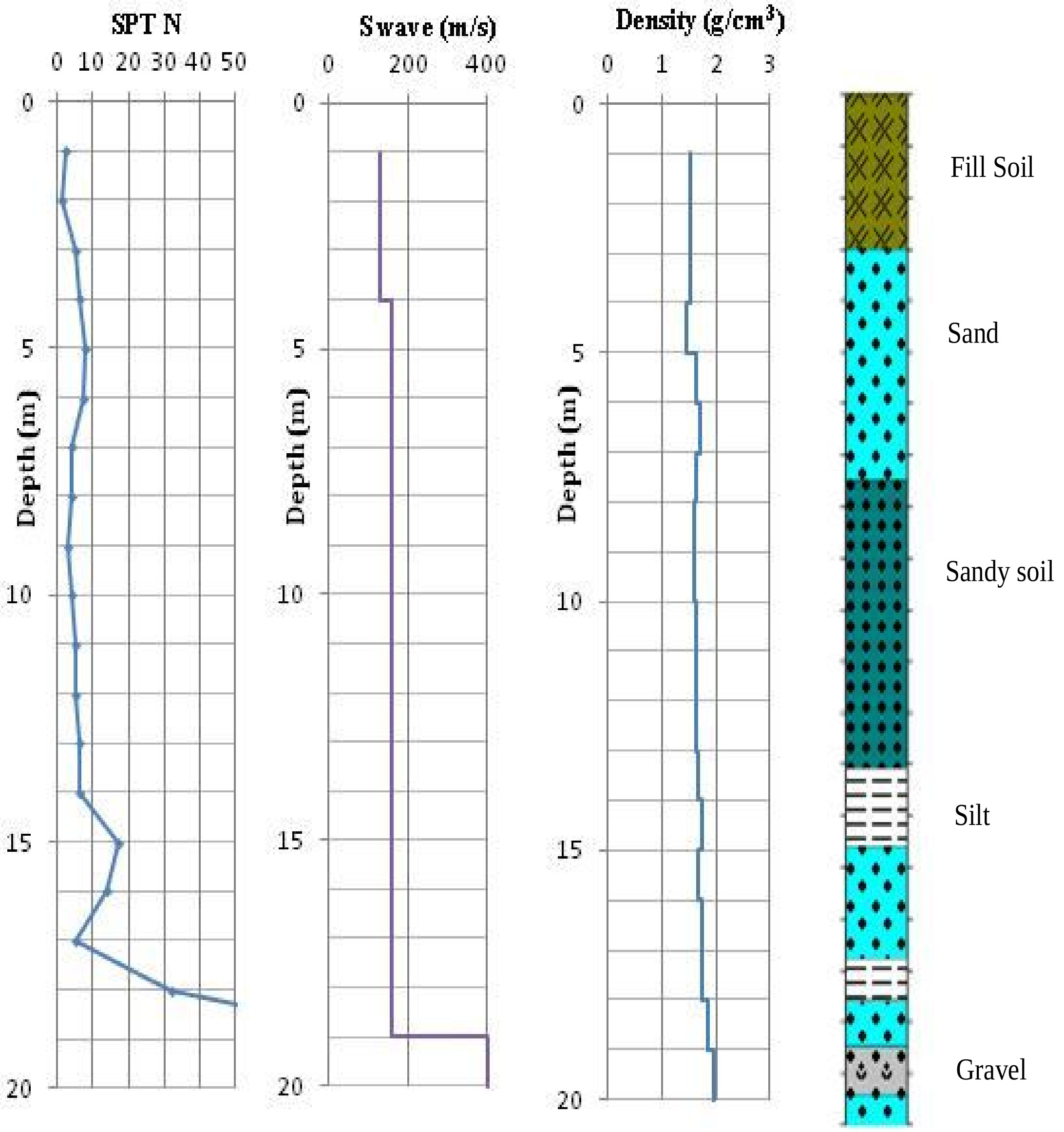

Figure 1: Typical soil condition at HRS019 station, Japan (modified after www.K-net.bosai.go.jp)

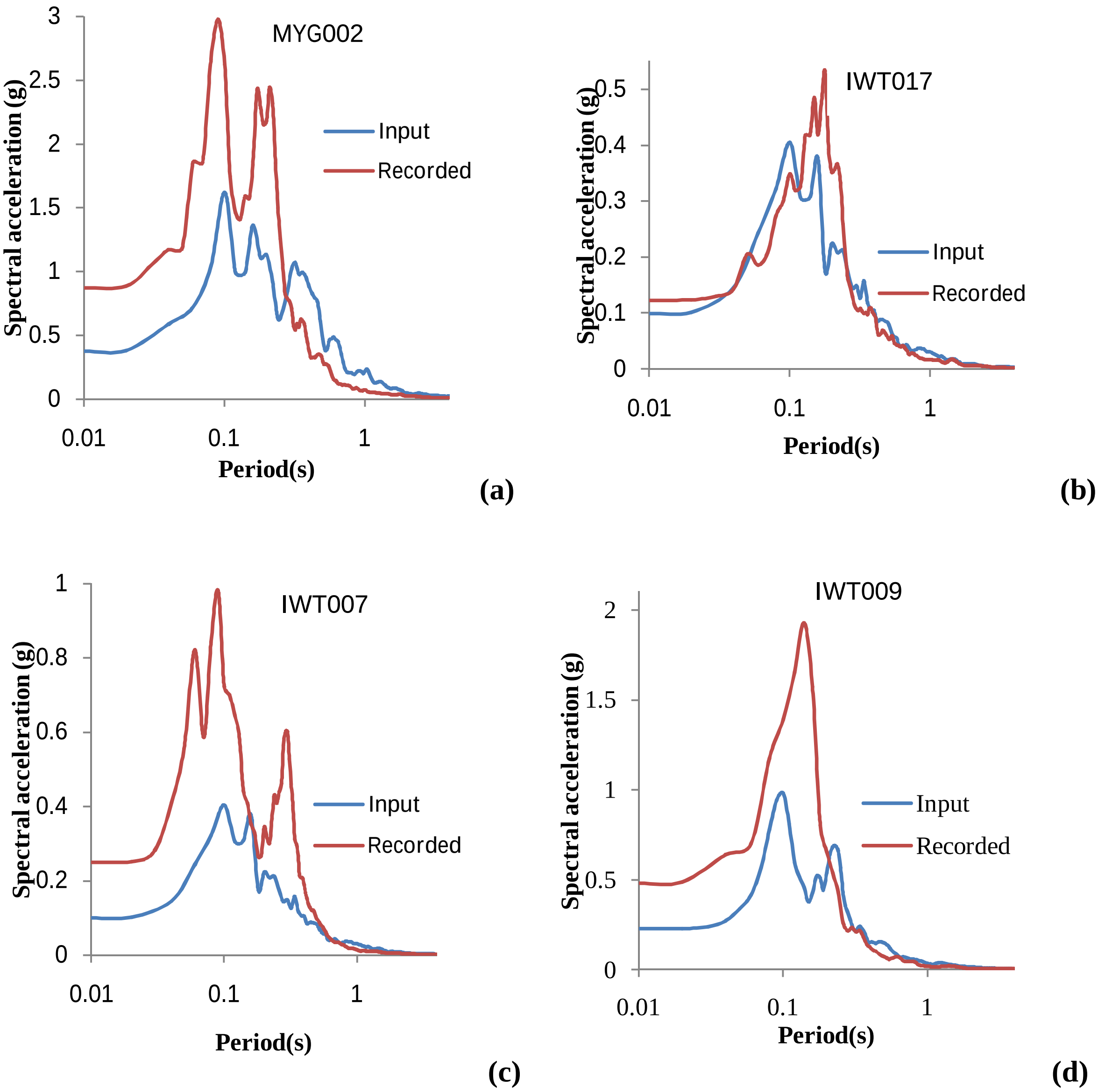

Figure 2: Variation of amplification in terms of response spectra for (a) sand profile MYG002 with M_w 7.0 (b) clay profile IWT017 with M_w 9.0(c) gravel profile IWT007 with M_w 7.2 (d) mixed profile IWT009 with M_w 6.8

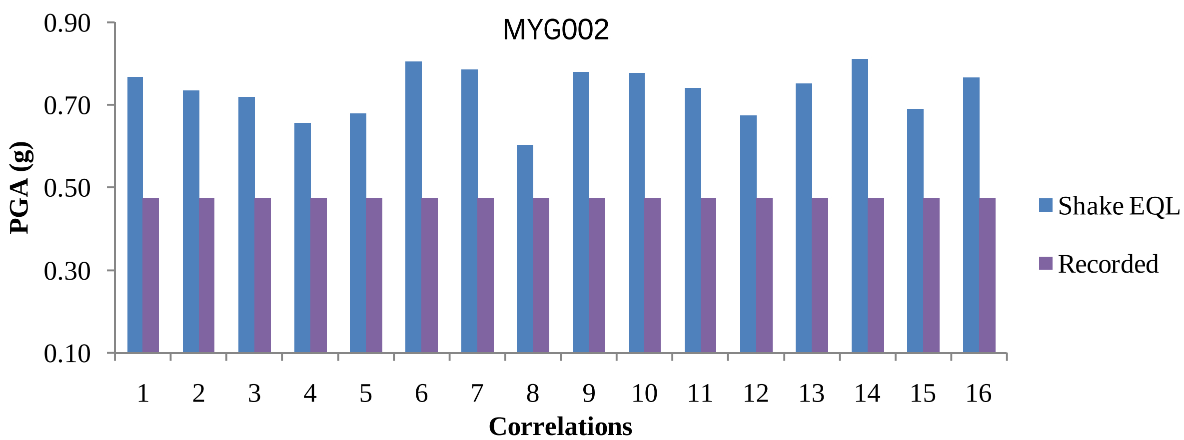

Figure 3: Typical plot of PGA variation for different correlations for sand profile MYG002 with magnitude 6.8

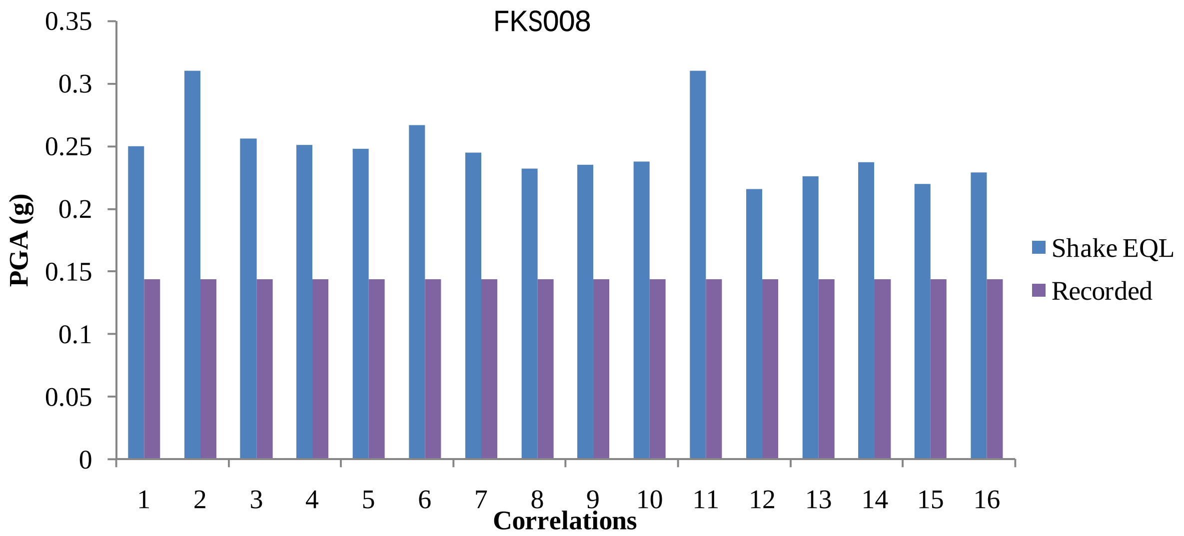

Figure 4: Typical plot of PGA variation for different correlations for clay profile FKS008 with magnitude 6.5

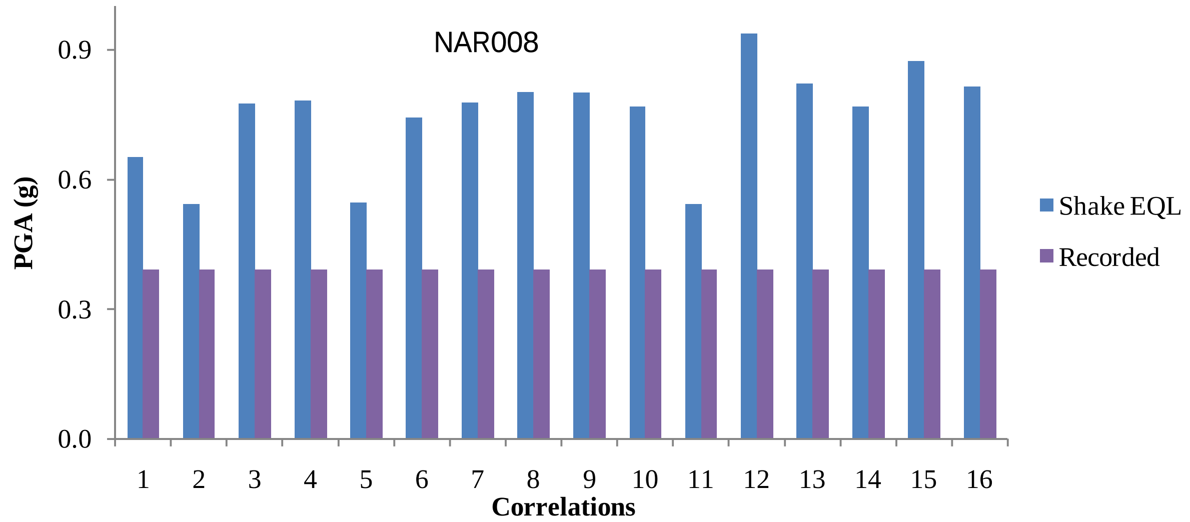

Figure 5: Typical plot of PGA variation for different correlations for gravel profile NAR008 with magnitude 5.5

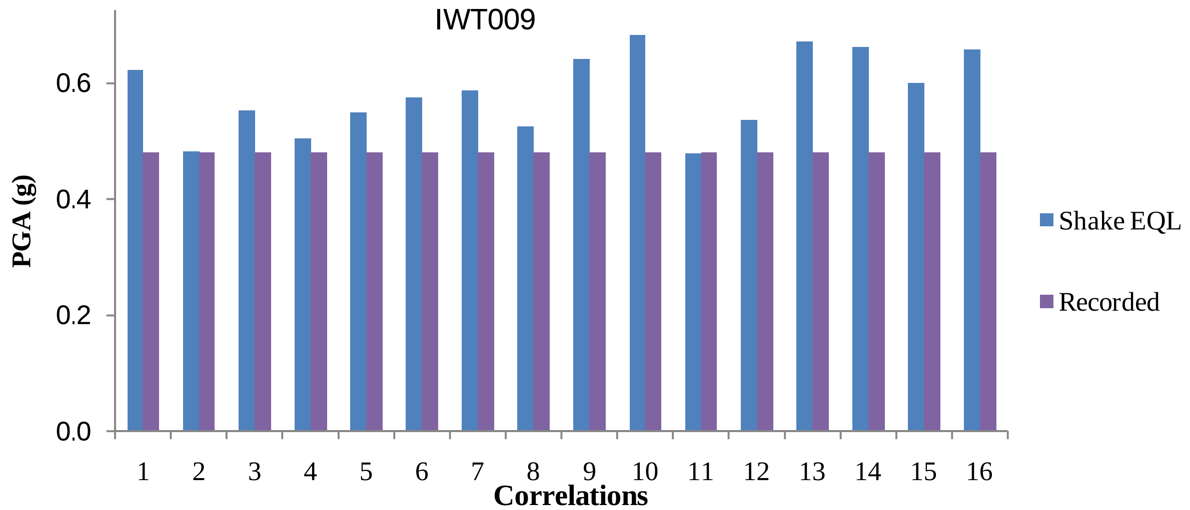

Figure 6: Typical plot of PGA variation for different correlations for mixed soil profile IWT009 with magnitude 6.8

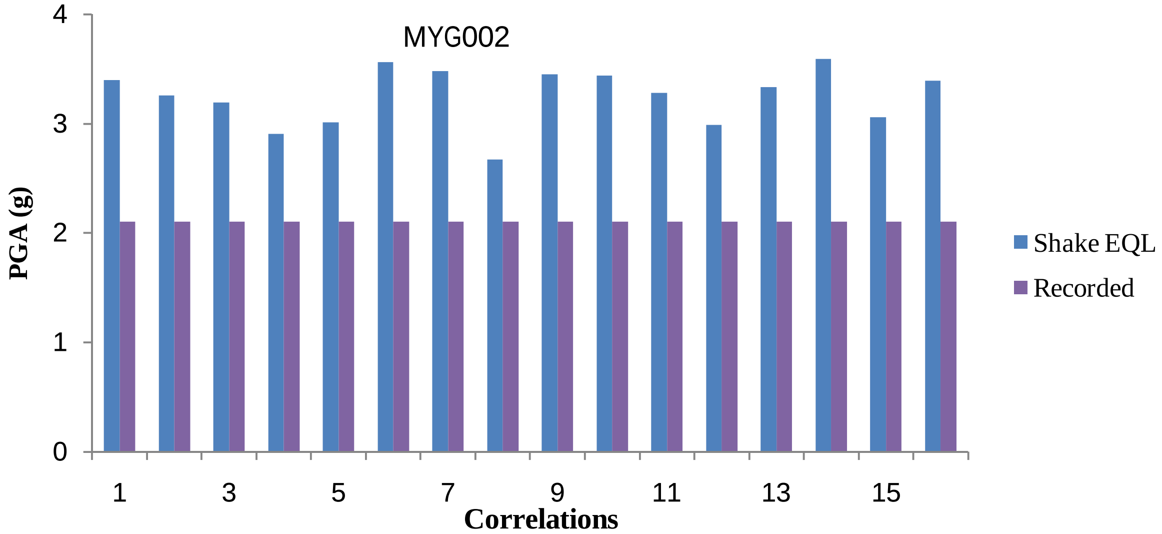

Figure 7: Typical plot of Variation of Amplification Factor with different correlation for sand profile MYG002 with magnitude 6.8

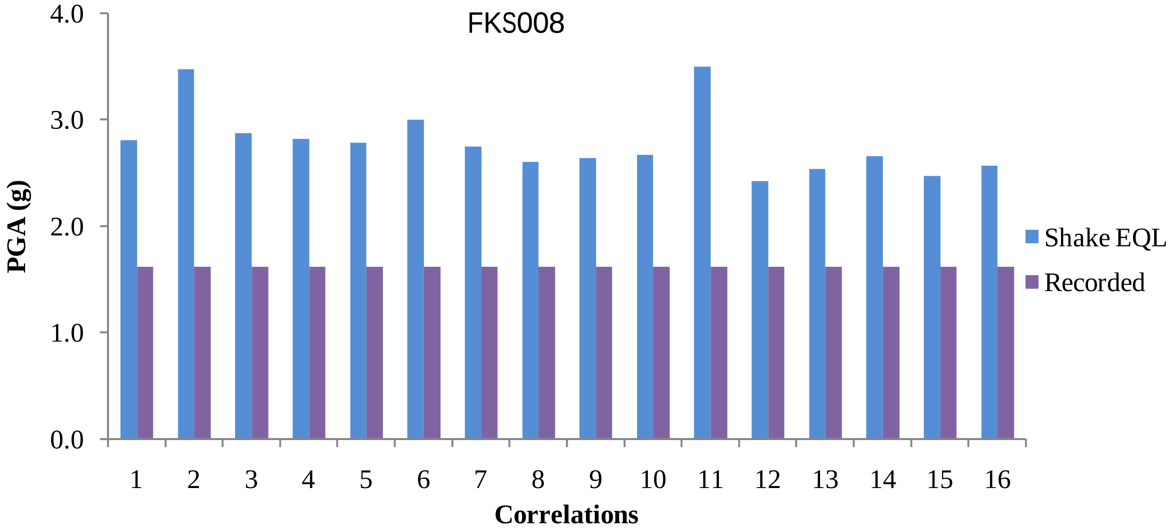

Figure 8: Typical plot of Variation of Amplification Factor with different correlation for clay profile FKS008 with magnitude 6.5

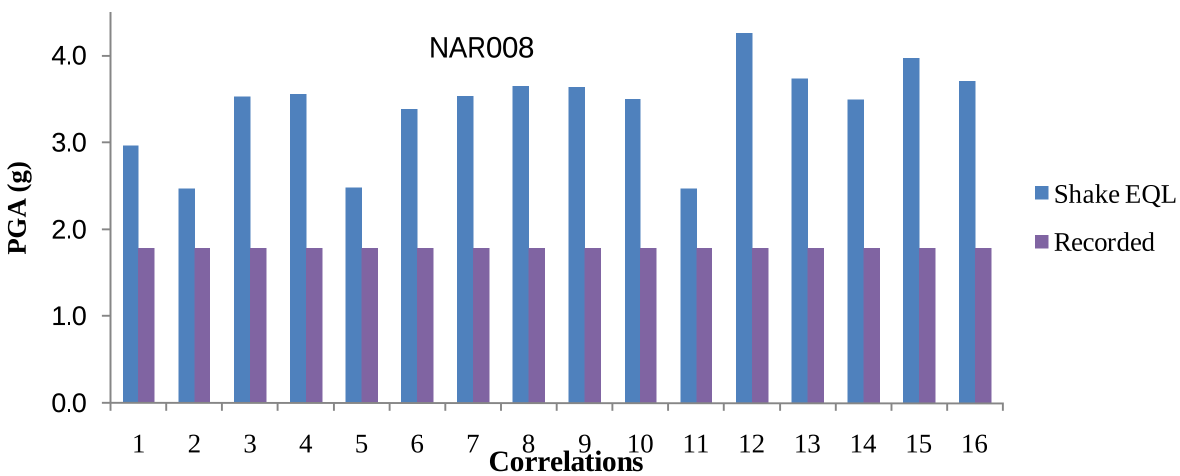

Figure 9: Typical plot of Variation of Amplification Factor with different correlation for Gravel profile NAR008 with magnitude 5.5

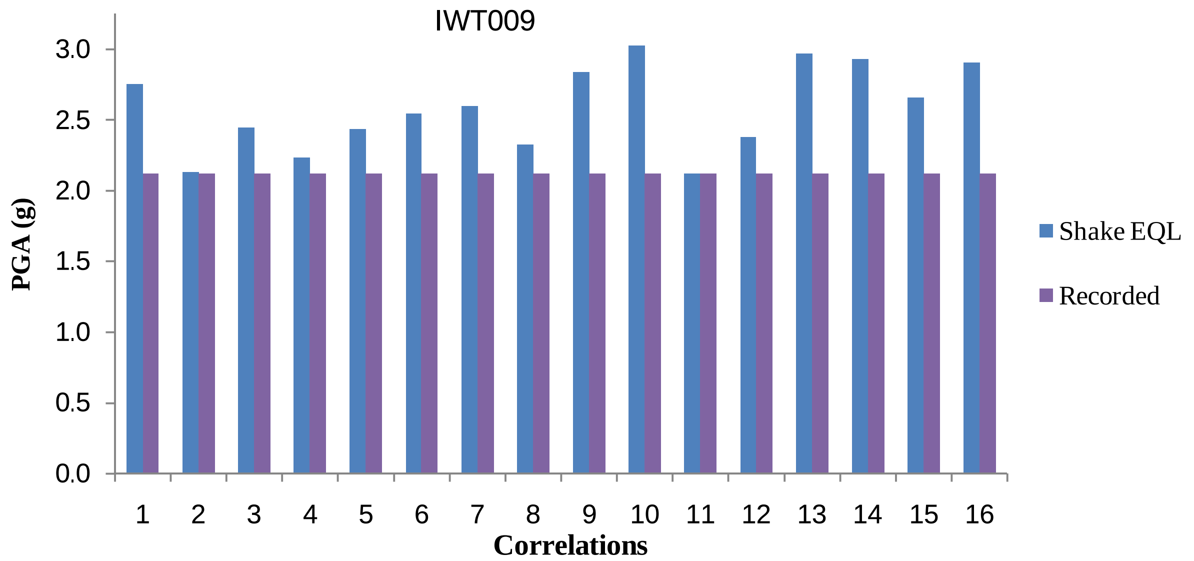

Figure 10: Typical plot of Variation of Amplification Factor with different correlation for mixed soil IWT009 with magnitude 6.8.

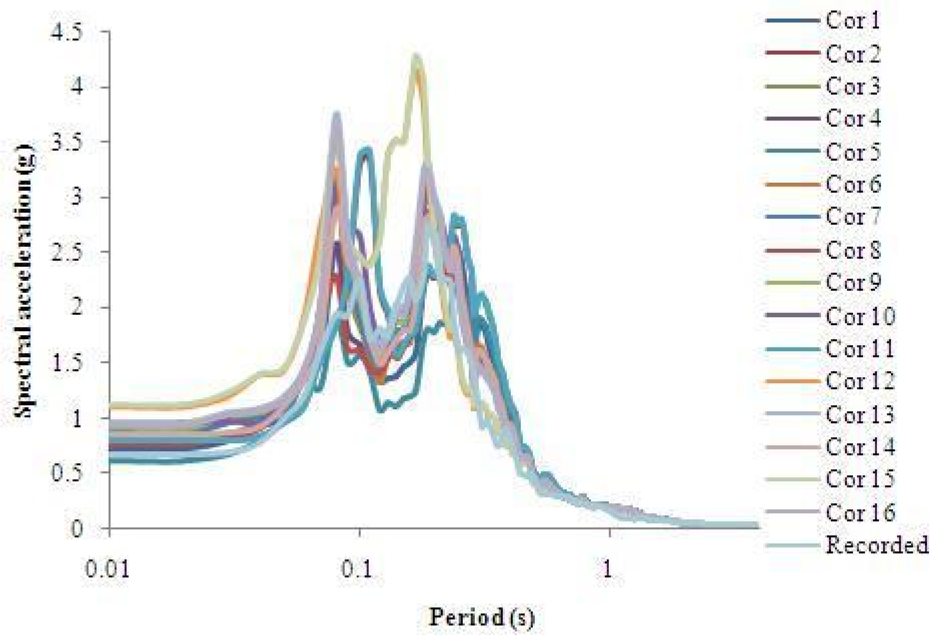

Figure 11: Typical plot of response spectrum for non-linear analysis of sand profile MYG002 with magnitude 9.0

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