Journal of Engg. Research **Vol. 4 No. (3) September 2016** pp. 18-42

اختيار ارتباط معامل القص لقيم اختبار الاختراق القياسي بناء على دراسات استجابة الموقع

،**أنبزاجان ب، *مانوهار د. ر.، **،سيد ش. ر. مصطفي**
وناصر س. ن. العريفي**
*قسم الهندسة المدنية، المعهد الهندي للعلوم، بنغالور، الهند
**قسم الجيولوجيا والجيوفيزياء، كلية العلوم، جامعة الملك سعود، الرياض، المملكة العربية السعودية
***قسم الزلازل، المعهد القومي للبحوث الفلكية والجيوفيزيقية، القاهرة، مصر

الخلاصة

يلعب معامل القص دورا أساسيا لتقدير معاملات استجابة الأرض في دراسات المنطقة الزلزالي. لا يزال الكثير من دراسات استجابة الموقع تتم باستخدام بيانات اختبار الاختراق القياسي معتبرا الارتباطات القائمة بين قيم اختبار الاختراق القياسي ومعامل القص دون معرفة فعالية ارتباط معامل القص لنوع عمود التربة. إلى حد علمنا، ليس هناك توجيه واضح المعالم بشأن استخدام ارتباط معامل قص مناسب لتقدير تمثيلية صلابة القص لعمود تربة معين في دراسات الاستجابة الأرضية المختلفة. لذلك، في هذه الدراسة قد بذلت محاولة لتحديد علاقة مناسبة لتقدير معامل القص (G_{max}) لأنواع مختلفة من التربة، مثل الرمل والطين والحصى أو خليط من كل الثلاثة. لقد تم تجميع واختيار مجموعة من البيانات الزلزالية المسجلة على سطح الارض (تتضمن عمود التربة جنبا إلى جنب مع بيانات اختبار الاختراق القياسي وقيم سرعة موجة القص) من شبكة K-NET اليابانية. لقد تألفت مجموعة البيانات التي تم جمعها من عدد من الزلازل التي سجلت على مسافات مختلفة وذات مقادير لحظية(M_W) تتراوح قيمها بين 5.0 و 9.0. وقد أجريت دراسات استجابة الموقع غير الخطية من خلال استخدام بيانات الزلازل المسجلة في موقع ذو طبيعة صخرية باعتبارها الحركة الأرضية المدخلة والمساهمة في خصائص التربة كما تم نشرها في موقع بيانات K-NET . وبناء علي ذلك، تم الحصول على الحركة الأرضية السطحية والاستجابة الطيفية وذلك باستخدام قيم ارتباط (G_{max}) المختلفة. ولقد تمت مقارنة النتائج المختلفة مع التسجيلات الزمنية السطحية التي سجلت لنفس الزلزال المدخل. وتبين هذه الدراسة أن ذروة التسارع الأرضي (PGA)، أطياف الاستجابة (RS) وعوامل التضخيم الموجية (AF) التي تم الحصول عليها من عدد قليل جدا من ارتباطات (G_{max}) قابلة للمقارنة مع قيم (PGA) المسجلة وطيف الاستجابة وعامل التضخيم.

Selection of shear modulus correlation for SPT N-values based on site response studies

Anbazhagan P.*,**, Manohar D. R.*, Sayed S. R. Moustafa**,*** and Nassir S. N. Al-Arifi**

**Department of Civil Engineering, Indian Institute of Science, Bangalore, India*

***Department of Geology and Geophysics, Faculty of Science, King Saud University, Riyadh, Saudi Arabia*

****Department of Seismology, National Research Institute of Astronomy and Geophysics (NRIAG), Cairo 11421, Egypt*

Corresponding author: anbazhagan@civil.iisc.ernet.in

ABSTRACT

Shear modulus plays a fundamental role in the estimation of the ground response parameters in seismic microzonation studies. A large number of site response studies are still being carried out using SPT data, considering existing correlations between SPT N-values and shear modulus without knowing the effectiveness of the shear modulus correlation for the type of soil column. To the best of our knowledge, there is no clear-cut guideline regarding the use of a suitable shear modulus correlation to estimate representative shear stiffness for a specific soil column in response studies. In this study, therefore, an attempt has been made to identify a suitable correlation for estimating shear modulus (G_{max}) for different types of soils, such as sand, clay and gravel or a mixture of all three. Sites with earthquake data recorded at the surface (soil profiles along with SPT N-values and shear wave velocity), are selected from the K-NET (Japanese website) data set. The collected earthquake data consists of moment magnitudes (Mw) ranging from 5.0 to 9.0, which were recorded at different epicentral distances. Nonlinear site response studies have been carried out by considering earthquake data recorded at a rock site as an input ground motion to the soil profiles, as published in the K-NET data site. Surface ground motion and response spectrums were further obtained from different G_{max} correlations and were compared with surface recorded time histories for the same event. This study shows that peak ground acceleration (PGA), response spectrums (RS) and amplification factors (AF) obtained from a very few G_{max} correlations are comparable with the recorded PGA, response spectrum and amplification factor.

Keywords: Amplification; correlation; shear modulus; site response; SPT-N-values.

INTRODUCTION

Seismic microzonation is an integrated approach to map different seismic hazards; of these site effects are predominantly studied because of their higher impact to the structural system damage. Regional microzonation maps are being developed considering site specific response parameters and liquefaction potential of the site (Anbazhagan *et al.,* 2012). Damage resulting from earthquakes mainly occurs because of changes in soil behaviour during earthquake loading. Subsurface soil layers play a very important role in the changes in seismic wave characteristics while they are travelling through the soil deposit. These are called "site effects" or "induced effects", and are primarily a function of the geotechnical properties of the subsurface materials (Anbazhagan *et al.,* 2012). Site effects are a combination of both soil and topographical effects, and result from the modification (amplification and deamplification) of the wave characteristics (amplitude, frequency content and duration) of the incoming wave field (Anbazhagan *et al.,* 2012). Amplification and liquefaction are the major effects of earthquakes in terms of causing damage to infrastructure and loss of life. Marano *et al.* (2010) from USGS notes that loss of life and damage caused by ground shaking hazards was more than 80 % of the total damage caused by deadly earthquakes in the last 40 years. Ground shaking modification is mainly due to the stiffness of the subsurface soil layers and the type and severity of earthquake damage is strongly influenced by the response of soils to cyclic loading. Parameters which characterize response studies are earthquake source, source nature and distance, wave path, geological context, upper soil properties, topography and primary site effects (Adams, 2007; Crow *et al.,* 2007).

The input soil parameters essential for each site/ground response analysis are thickness (h), density (ρ), and shear modulus (G_{max}) of each subsurface layer. The shear modulus of each layer is one of the most important site parameters affecting site response studies along with the depth of the bedrock and the type of sand or clay (Hwang & Lee, 1991). Borehole drilling and logging of borehole information (bore logs) are useful in determining the soil type and thickness of each layer. Undisturbed soil samples collected from boreholes are used to estimate the in-situ density of each layer. However, Ohsaki & Iwasaki (1973) highlight such measuring techniques are expensive, time consuming and require more specialized equipment.

Bore logs with standard penetration test (SPT) N-values are widely used in microzonation studies in particular to estimate low strain shear modulus (G_{max}) by adopting existing correlations between SPT N-values and shear modulus. Shear modulus (G_{max}) derived from correlations, modulus reduction and damping curves should represent the in-situ soil behaviour and be close to site-specific values. However, in practice they are often chosen without justification: for example, when SPT N is used to arrive at dynamic properties, just a few G_{max} correlations are routinely used for most of the response studies (Anbazhagan *et al.,* 2012).

Therefore, in this paper, an attempt has been made to identify suitable G_{max} correlations for specific soil column types, so as to support effective site response analysis. The major soil column types considered in this study are sand, clay, gravel and a mixture of all three. The selected sites have recorded data at the surface as well as drilled soil profiles with SPT N-values. The earthquake data collected consists of moment magnitudes (Mw) ranging from 5.0 to 9.0, recorded at different epicentral distances. Surface ground motion and response spectrums are obtained from different G_{max} correlations and are compared with the surface recorded earthquake data for the same event. The study finds suitable G_{max} correlation by comparing estimated peak ground acceleration (PGA), response spectrums (RS) and amplification factor (AF) with respective recorded values.

EXISTING SHEAR MODULUS CORRELATIONS

Many empirical correlations have been developed between low strain dynamic properties of soil, such as shear wave velocity and shear modulus on the one hand, and SPT N-values on the other. Shear wave velocity correlations are particularly widely used, but there are fewer shear modulus correlations (Anbazhagan *et al.,* 2012). Anbazhagan *et al.* (2012) presented a detailed review of the fourteen available G_{max} correlations with SPT N and a proposed set of new correlations applicable worldwide. They pointed out that the existing correlations were developed some considerable time ago by Imai & Yoshimura (1970), Ohba & Toriumi (1970), Ohta *et al.* (1972), Ohsaki & Iwasaki (1973), Hara *et al.* (1974), Imai & Tonouchi (1982) and Anbazhagan & Sitharam (2010). The Imai & Tonouchi (1982) correlation for clay was modified by Kramer (1996) for sandy soil by replacing the measured N-values with energy corrected N-values [N_{60}] (Anbazhagan *et al.,* 2012). A set of new shear modulus correlations were developed by Anbazhagan *et al.,* (2012) considering measured data from Ohta *et al.* (1972), Hara *et al.* (1974) and Anbazhagan & Sitharam (2010). Shear modulus correlations proposed by Seed *et al.* (1983), Seed *et al.* (1986) and Kramer (1996) are inbuilt into SHAKE2000 (Schnabel *et al.,* 1972) and are widely used to calculate the shear modulus using SPT N-values for site response analysis. Among the inbuilt correlations in SHAKE2000, Seed *et al.*'s (1983) correlation was based on their previous studies and the Seed *et al.* (1986) correlation was based on data from Ohta & Goto (1976). These correlations require additional parameters other than the SPT N-value to estimate shear modulus and hence are not widely used in ground response studies. In this study, a set of compatible and reliable 16 G_{max} correlations are selected for the site response study, so that suitable G_{max} correlations can be identified for each soil type. Table 1 presents the 16 SPT N versus G_{max} correlations with equation numbers used in the study.

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

Eq. No	Correlations from different authors selected from literature	Correlations in SI unit (MPa)	Remarks
1	Imai & Yoshimura (1970)	$G = 9.81N^{0.78}$	Mixed soil type
2	Ohba & Toriumi (1970)	$G = 11.96N^{0.62}$	Alluvial soil type
3	Ohta *et al.* (1972)	$G = 13.63N^{0.72}$	Tertiary soil, diluvial sandy and cohesive soil
4	Ohsaki & Iwasaki (1973)	$G = 11.94N^{0.78}$	All soil types
5	Ohsaki & Iwasaki (1973)	$G = 6.374N^{0.94}$	Sandy soil
6	Ohsaki & Iwasaki (1973)	$G = 11.59N^{0.76}$	Intermediate soil
7	Ohsaki & Iwasaki (1973)	$G = 13.73N^{0.71}$	Cohesive soil
8	Ohsaki & 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 & Tonouchi (1982)	$G = 17.26N^{0.607}$	Alluvial clay
11	Imai & Tonouchi (1982)	$G = 12.26N^{0.611}$	Alluvial Sand
12	Imai & Tonouchi (1982)	$G = 24.61N^{0.555}$	Diluvial clay
13	Imai & Tonouchi(1982)	$G = 17.36N^{0.631}$	Diluvial Sand
14	Imai & Tonouchi (1982)	$G = 14.12N^{0.68}$	All soil types
15	Anbazhagan & Sitharam (2010)	$G = 24.28N^{0.55}$	Silty sand with less percentage of clay
16	Anbazhagan *et al.* (2012)	$G = 16.40N^{0.65}$	Data from Ohta *et al.* (1972) & Hara *et al.* (1974) and Anbazhagan and Sitharam (2010)

SOIL PROFILE AND GROUND MOTION DATA

Soil profile and ground motion data were collected from the K-NET database. K-NET (http://www.kyoshin.bosai.go.jp/) is a strong-motion seismograph network that consists of pairs of seismographs installed in a borehole together with high sensitivity seismographs on the ground surface, deployed at approximately 700 locations nationwide in Japan. K-NET has been operated by the National Research Institute for Earth Science and Disaster Prevention (NIED) since June, 1996. NIED constructed the K-NET under the plan 'Fundamental Survey and Observation for Earthquake Research' directed by 'the Headquarters for Earthquake Research Promotion'. The K-NET database consists of acceleration time history from strong motion seismographs installed in a borehole as well as on the ground surface, along with subsurface soil/rock information with shear wave velocities. The K-NET subsurface information includes stratification details, P-wave velocity profiles and S-wave velocity profiles. Sites with earthquake data recorded at the surface, drilled soil profiles with SPT N-values and shear wave velocity are selected for this study. The magnitude scale used in K-NET is M_{JMA}, estimated by the Japan Metrological Agency (JMA). A total of five profiles of sand, three profiles of clay, five profiles of gravel and eleven profiles of mixed soil type for different magnitudes of earthquakes in Japan have been downloaded and used. A summary of the soil profiles used for the analysis is given in Table 2. A typical soil profile is presented in Figure 1. Figure 2 shows the location of different soil profiles used for the analysis. Table 3 presents the details of the N-values for different stations with their depth.

Table 2. Details of soil profile used for the analysis

Soil Column	**Station**	**Site Class**	**Vs^{30} (m/s)**	**Earthquake Magnitude (M_w)**	**Depth of Input motion (m)**	**Surface recorded 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	0.17
	MYG002	C	469	6.8,5.1,6.4,7.0, 7.2,9.0	10.00	0.48,0.29,0.36,0.8 7,0.51,0.67
	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	0.12,0.12,0.14,0.1 5,1.03
	HRS005	C	440	6.4	12.44	0.29
	IWT017	C	437	6.8,7.2,9.0	10.15	0.30,0.12,0.33
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	0.48,0.17,0.27,0.2 9,0.58
	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

Vs^{30} – the average shear-velocity down to 30 m

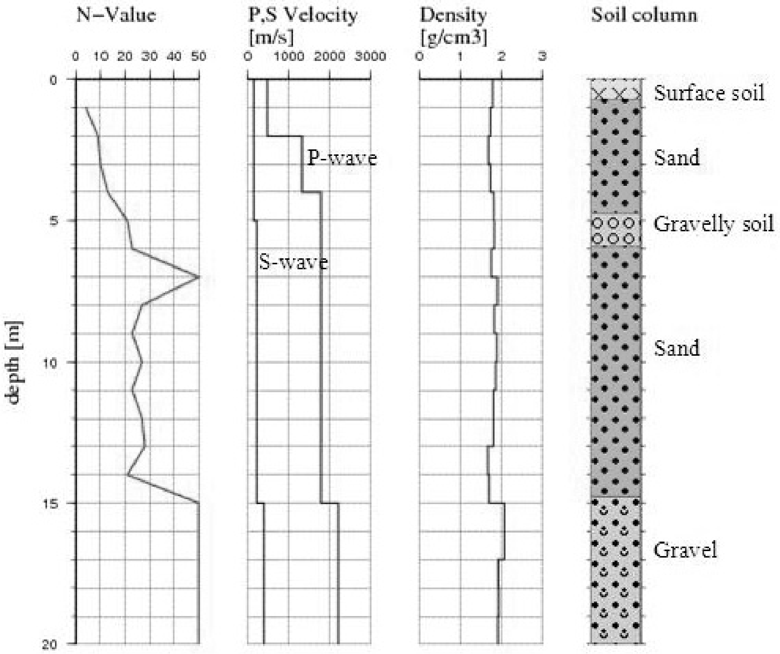

Fig. 1. Typical soil profile at HRS019 station, Japan (modified after www.K-net.bosai.go.jp)

Strong motion data of acceleration of above 0.05 g are of primary interest for engineers (Chen & Scawthorn, 2003). Accelerations of less than 0.05 g will have moderate perceived shaking and very light potential to damage structures. Therefore, in the present study, accelerations of greater than or equal to 0.05 g are considered. From the point of view of analysis, earthquakes with magnitudes greater than 5.0 are selected, since lower magnitude earthquakes have bedrock PGA values of 0.05 g and less. The magnitude range in this study varies from 5.0 to 9.0 (Table 2). The sites selected for the analysis have amplification in ground motion, when compared to bedrock motion. Most surface recorded ground motion with soil profiles and SPT N-values does not have the ground motion data recorded at bedrock. Hence, in this study, it has been considered that ground motion data recorded at site classes A or B is free from amplification and this is used as an input motion for other sites. Data from K-NET was selected and used as an input motion for sites C, D, E and F, where the surface recorded ground motion is available. For the strong motion data obtained from online records, baseline correction was applied and the acceleration time histories were multiplied by the scale factor cited in the header file of the recorded ground motion data file. These corrected acceleration time histories were used to generate response spectra and compared. The response spectrum describes the maximum response of a single-degree-of-freedom (SDOF) system to a particular input motion as a function of the natural frequency and damping ratio of the SDOF system. The response may be expressed in terms of acceleration, velocity or displacement. When the Duhamel integral is applied to a linear elastic SDOF system, it produces expressions for the acceleration time histories. Figure 3 shows typical spectra of ground motions for site classes A/B (used as input motions) and surface recorded ground motions for the same earthquake for different sites considered in the analysis.

Fig. 2. Locations of different stations used for analysis.

Table 3. Details of N values for different station with depth

	N-Value for different sites																							
Depth (m)	**MYG002**	**EHM006**	**MYG003**	**MIE008**	**HRS019**	**FKS008**	**HRS005**	**IWT017**	**EHM002**	**IWT023**	**NAR004**	**NAR008**	**IWT007**	**MIE010**	**FKS007**	**IWT004**	**IWT009**	**EHM012**	**MIE011**	**EHM009**	**IWT001**	**EHM003**	**EHM010**	**WKY005**
1.0	3	7	99	7	4	6	7	3	27	18	8	13	7	13	8	10	28	13	2	9	8	4	15	12
2.0	3	50	4	7	9	6	22	7	35	20	12	8	99	15	27	10	99	11	3	9	7	3	14	18
3.0	6	99	7	8	10	10	28	4	99	99	17	4	25	14	36	4	12	8	20	45	11	6	11	15
4.0	24	99	8	6	13	10	24	5	99	99	11	36	17	10	38	4	16	9	40	18	2	7	12	6
5.0	26	99	32	4	21	7	21	5	99	33	99	99	28	10	17	5	27	99	99	14	22	5	23	14
6.0	99	99	37	7	23	34	36	15	99	99	99	99	30	13	99	29	99	99	99	30	99	6	27	99
7.0	99	99	99	8	50	46	32	6	99	99	99	49	46	16	99	2	99	99	99	7	99	28	18	99
8.0	99	99	99	6	27	99	34	34	99	99	99	99	34	15	99	13	99	99	99	13	99	45	30	99
9.0	99	99	99	9	23	99	99	99	99	99	99	99	99	11	99	5	99	99	99	99	99	33	27	99
10.0	99	99	99	9	27	99	45	99	99	99	99	99	99	25	99	23	99	99	99	99	99	32	42	99
11.0				9	23		99						99	25		11				99		15	32	
12.0				8	27		99						99	25		12						15	99	
13.0				12	28								99	41		16						30	47	
14.0				40	21								99	35		14						99	34	
15.0				48	50								99	41		18						35	99	
16.0					50								32	39		23						99	99	
17.0					50								99	99		20						99		
18.0					50								99	31		50								
19.0					50								99	30		35								
20.0					50								99	99		50								

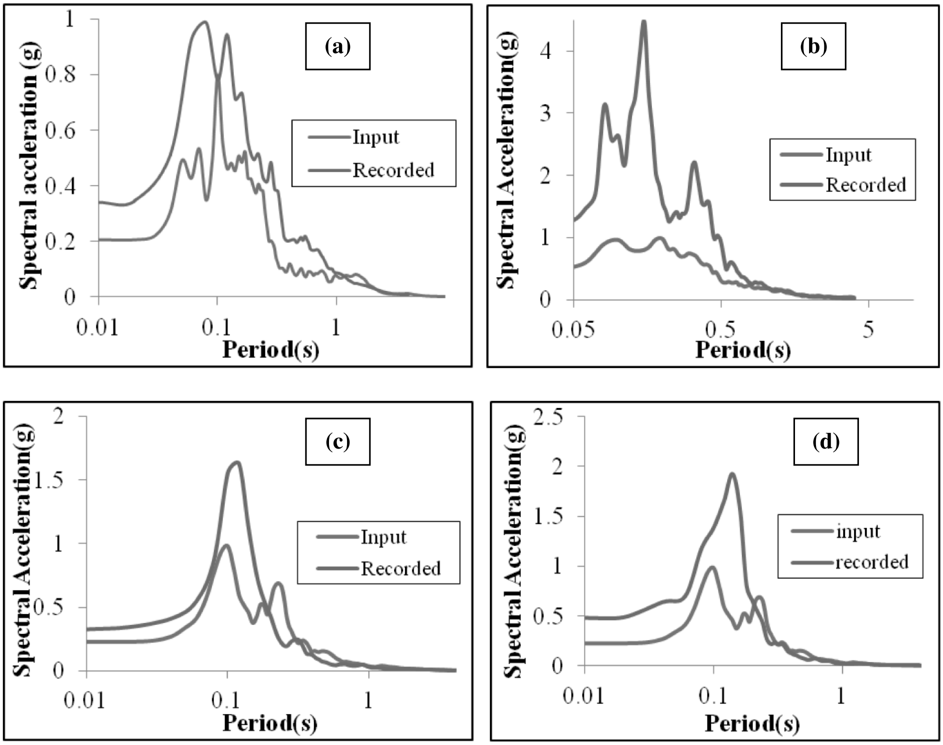

Fig. 3. Selected response spectra input and surface recorded used in the study (a) sand profile EHM006 with M_w 6.4 (b) clay profile FKS008 with M_w 9.0(c) gravel profile IWT023 with M_w 6.8 (d) mixed profile IWT009 with M_w 6.8

SITE RESPONSE STUDY TO SELECTED G_{max} RELATIONS

Site-specific ground response analysis is focused on determining the amplification of seismic waves due to local site specific soil layers. A site response analysis is generally performed using correlations between SPT N and shear modulus (G_{max}), through 1-D equivalent linear and nonlinear models. In this study, equivalent linear (EQL) analysis was carried out using the SHAKE site response program (Schnabel *et al.,* 1972) and DEEPSOIL, and nonlinear analysis was carried out using DEEPSOIL (Hashash *et al.,* 2012). Soil response under irregular cyclic loading for SHAKE is modelled 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 the use of equivalent linear soil properties through an iterative procedure to obtain values for modulus and damping that are compatible with the effective strains in each layer in the equivalent linear analysis. The 1-D EQL analysis to compute ground response using DEEPSOIL employs an iterative procedure in the selection of shear modulus and damping ratio of soil properties. These properties can be defined by discrete points or by defining soil parameters that used to be in the hyperbolic model in nonlinear analysis. DEEPSOIL uses the Matasovic Kondner and Zelasko backbone curve (Matasovic & Vucetic, 1993) which modifies hyperbola, while viscous damping is incorporated via the Rayleigh damping formulation. In this study, shear modulus and damping curves proposed by Seed & Idriss (1970) for sand, Vucetic & Dobry (1991) for clay, Seed *et al.* (1986) for gravel, and Schnabel (1973) for rock are used for each analysis for all G_{max} correlations. For mixed soil deposits, the respective modulus and damping curves were used for the particular soil type in the soil column. 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 for all the analyses. Detailed equivalent linear analysis and results are presented in Anbazhagan *et al.* (2015).

EQUIVALENT LINEAR (EQL) AND NONLINEAR (NL) ANALYSIS RESULTS

Initially EQL and NL were carried out for a few selected profiles and the estimated PGA and AF by EQL and NL were compared with corresponding values recorded at the selected site. The PGA obtained from the site response analysis considering the 16 G_{max} correlations discussed in the previous section were compared with the recorded PGA values at the surface. Typical plots of the PGA variation obtained from the 16 G_{max} correlations are given in Figure 4 for both the EQL and NL analysis. The selected profiles show that EQL analysis by SHAKE and DEEPSOIL predicts higher PGA values than NL analysis by DEEPSOIL, with the latter being close to the recorded values. Similarly the amplification factor was compared with selected profiles from the EQL and NL analyses. The term "Amplification Factor" (AF) used here refers to the ratio of the PGA at the ground surface to the PGA at the bedrock, as per Anbazhagan *et al.* (2013). Typical estimated amplification values from the EQL and NL analyses for the selected sites are shown in Figure 5. It can be noted from this figure that the amplification factor estimated using input and surface recorded ground motion is around 1.31. Whereas, the AF values from the EQL analyses are more than 2.0, and the AF values from the NL analyses are in the range of 1.3 to 2.0. Comparisons of PGA and AF between recorded and calculated ground motions through EQL and NL analysis for typical sites of each soil type (MIE008-sand, IWT017-clay, EHM0002-gravel and MIE010-mixed soil type) are shown in Table 4. It can be noticed from Figures 4 and 5 (comparison of PGA and AF with recorded values for site IWT017, along with response studies carried out through EQL and NL analyses, considering all 16 shear modulus correlations) and Table 4, that the PGA and AF values estimated by the EQL models using 16 G_{max} correlations are considerably higher than the NL model results. The PGA and AF values derived from most of G_{max} correlations are well comparable with those from the NL analysis.

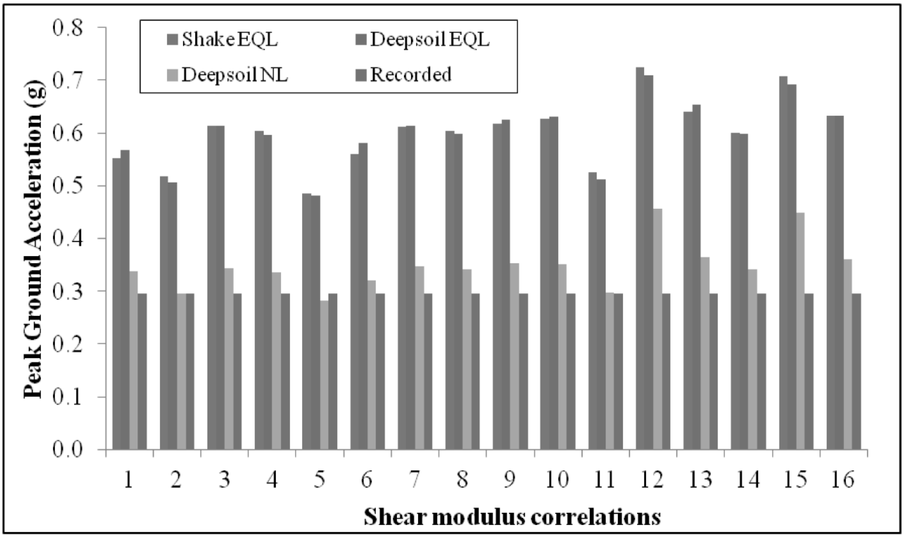

Fig.4. Comparison of PGA values from G_{max} correlations by EQL and NL analysis for typical site (IWT017)

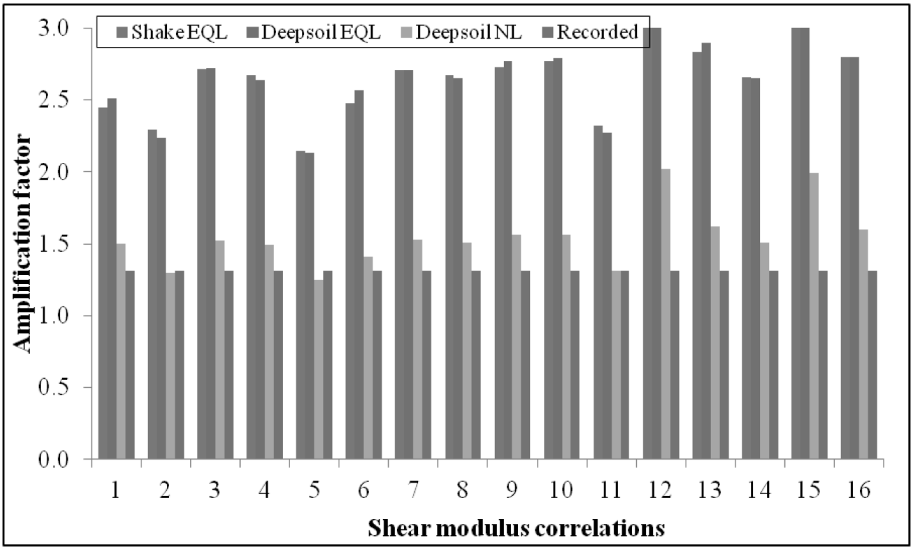

Fig.5. Comparison of amplification factor from G_{max} correlations by EQL and NL analysis for typical site (IWT017)

Table 4. Comparison of recorded and calculated peak ground acceleration (PGA) and amplification factor (AF)

Station	Magnitude (M_w)	Recorded PGA(g)	Recorded AF	Eq. no	Calculated PGA(g)			Calculated AF		
					EQ Shake	EQ DeepSoil	NL DeepSoil	EQ Shake	EQ DeepSoil	NL DeepSoil
MIE008	7.4	0.166	1.22	1	0.228	0.341	0.163	1.68	2.51	1.20
				2	0.227	0.284	0.161	1.67	2.09	1.18
				3	0.312	0.300	0.214	2.29	2.21	1.58
				4	0.307	0.298	0.213	2.26	2.19	1.56
				5	0.214	0.286	0.153	1.57	2.10	1.12
				6	0.277	0.323	0.177	2.03	2.38	1.30
				7	0.306	0.298	0.212	2.25	2.19	1.56
				8	0.319	0.302	0.214	2.34	2.22	1.58
				9	0.320	0.303	0.214	2.35	2.23	1.58
				10	0.312	0.300	0.211	2.30	2.21	1.55
				11	0.228	0.287	0.162	1.68	2.11	1.19
				12	0.302	0.382	0.210	2.22	2.81	1.55
				13	0.325	0.308	0.226	2.39	2.26	1.66
				14	0.288	0.299	0.201	2.12	2.20	1.48
				15	0.295	0.373	0.213	2.17	2.74	1.57
				16	0.324	0.304	0.221	2.39	2.24	1.63
IWT017	6.8	0.296	1.3	1	0.553	0.567	0.338	2.45	2.51	1.50
				2	0.518	0.506	0.295	2.29	2.24	1.30
				3	0.613	0.615	0.344	2.71	2.72	1.52
				4	0.604	0.596	0.337	2.67	2.64	1.49
				5	0.485	0.481	0.283	2.14	2.13	1.25
				6	0.560	0.581	0.320	2.48	2.57	1.41
				7	0.612	0.613	0.347	2.71	2.71	1.53
				8	0.604	0.599	0.341	2.67	2.65	1.51
				9	0.617	0.625	0.353	2.73	2.77	1.56
				10	0.626	0.631	0.352	2.77	2.79	1.56
				11	0.525	0.513	0.297	2.32	2.27	1.31
				12	0.724	0.710	0.457	3.20	3.14	2.02
				13	0.640	0.654	0.365	2.83	2.90	1.62
				14	0.601	0.599	0.341	2.66	2.65	1.51
				15	0.707	0.692	0.449	3.13	3.06	1.99
				16	0.632	0.634	0.361	2.80	2.80	1.60

EHM002	6.4	0.211	1.34	1	0.772	0.721	0.797	4.89	4.57	5.05
				2	0.679	0.609	0.668	4.30	3.85	4.23
				3	0.690	0.625	0.737	4.37	3.95	4.67
				4	0.653	0.642	0.594	4.13	4.06	3.76
				5	0.746	0.587	0.708	4.72	3.71	4.48
				6	0.691	0.671	0.728	4.37	4.25	4.61
				7	0.750	0.648	0.730	4.75	4.10	4.62
				8	0.724	0.661	0.648	4.58	4.18	4.10
				9	0.693	0.686	0.690	4.38	4.34	4.37
				10	0.594	0.537	0.604	3.76	3.40	3.82
				11	0.702	0.644	0.694	4.44	4.08	4.39
				12	0.687	0.637	0.639	4.35	4.03	4.04
				13	0.673	0.640	0.661	4.26	4.05	4.18
				14	0.721	0.675	0.652	4.57	4.27	4.12
				15	0.685	0.656	0.678	4.34	4.15	4.29
				16	0.737	0.704	0.633	4.67	4.46	4.01
MIE010	7.4	0.154	1.13	1	0.191	0.192	0.168	1.41	1.41	1.23
				2	0.172	0.174	0.144	1.27	1.28	1.06
				3	0.221	0.220	0.167	1.62	1.62	1.23
				4	0.228	0.228	0.183	1.68	1.67	1.34
				5	0.203	0.204	0.165	1.50	1.50	1.21
				6	0.212	0.212	0.162	1.56	1.56	1.19
				7	0.215	0.214	0.167	1.58	1.58	1.23
				8	0.225	0.225	0.195	1.66	1.66	1.43
				9	0.210	0.209	0.161	1.55	1.54	1.18
				10	0.208	0.210	0.155	1.53	1.54	1.14
				11	0.171	0.173	0.144	1.26	1.27	1.06
				12	0.224	0.224	0.172	1.65	1.64	1.26
				13	0.208	0.207	0.158	1.53	1.52	1.16
				14	0.207	0.209	0.158	1.52	1.54	1.16
				15	0.222	0.221	0.165	1.63	1.63	1.21
				16	0.210	0.209	0.159	1.54	1.54	1.17

In this analysis, since all input parameters and soil models are similar for the EQL and NL analyses, it is assumed that the higher PGA and AF values in the EQL analysis were due to the numerical scheme. The dynamic responses computed via these methods can vary considerably due to inherent differences in the numerical approaches (frequency domain vs. time domain solutions) and differences in how the nonlinear soil response is modelled (equivalent linear vs. fully nonlinear). The smaller amplification predicted by the nonlinear method is probably due to the continuously changing soil stiffness in the nonlinear analysis (Rathje & Kottke, 2011). However, there may be additional reasons apart from the numerical scheme, which is not the focus of this paper. From the results it is believed that NL analysis using the DEEPSOIL program is appropriate for the estimation of response parameters that are close to recorded values. Henceforth, only nonlinear analysis is used to evaluate seismic response for all the profiles considered in this study. The response spectrum (RS) at the top layer derived from nonlinear site response analysis by considering 16 G_{max} correlations is shown in Figure 6. It can be noticed from Figure 6 that the shape of the response spectrum is similar for all the G_{max} correlations, but the amplitudes are different and the response spectra of very few correlations matches with the recorded spectra across the entire period range.

SELECTION OF G_{max} CORRELATION BASED ON PGA

Nonlinear site response analysis by DEEPSOIL was carried out for all profiles given in Table 2. The PGA values estimated using 16 G_{max} correlations were compared with the surface recorded PGA values for each site and, in this section, the G_{max} correlations, which give PGA values closest to the recorded PGA values for the most sites and magnitudes are identified. The PGA values obtained from different correlations were compared with recorded PGA values under five groups of percentage error varying from 0 to ±50% with intervals of ±10% error.

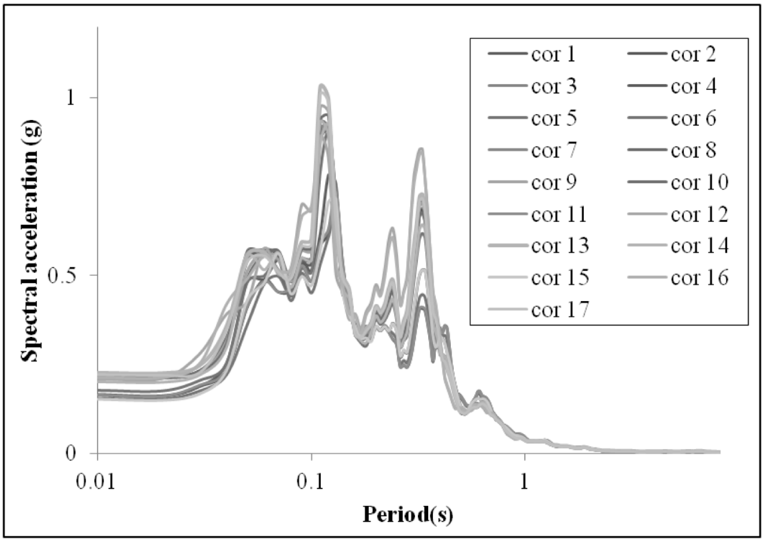

Fig. 6. Typical plot of response spectrum from non-linear analysis of sand profile MIE008 with magnitude 7.4

The variation of the PGA values from the recorded data and from calculated responses are shown in Figures 7-10 for each soil type. Table 5 shows the comparison of PGA and AF values obtained from different correlations with the recorded value through NL analysis for all the sites considered in this study.

For shallow sand profile of MYG002 (4 m), correlations 4, 8 and 12 predict close to the recorded value with an error of ±0-10% for a magnitude 9.0 earthquake (Figure 7). For the clay profile IWT017, where the depth of the clay is around 8 m, correlations 2, 5, 8 and 11 predict an error of ±0-10% for most of the magnitudes considered in this study (Figure 8). Figure 8 also shows that the PGA values of the clay profile IWT017 with an earthquake magnitude of 6.8 have an error of ±0-10% for G_{max} correlations 2, 5 and 11. For the gravel profile IWT007 all correlations predict well for an earthquake magnitude of 7.2, but correlations 2, 10, 12, 13 and 15 have the lowest error rate of ±0-10% (Figure 9). In the mixed soil type of site MIE010, which comprises clay layer in-between sand and with filled-up soil on top, correlations 2, 11 and 5 return errors of ±0-10% for a magnitude 7.4 earthquake (Figure 10). For the same profile with a magnitude 6.9 earthquake, correlations 2 and 11 predict good estimates (Table 5). G_{max} correlations, which predict PGA values that are close to the recorded PGA values for each site and different magnitudes are highlighted in Table 5. From the table it can be observed that G_{max} correlation 8 for sand, 2 for clay, 10 for gravel and 11 for mixed soil predict close to the recorded data for the maximum number of cases for the respective soil column above bedrock. The next best G_{max} correlations are 12 for sand, 11 for clay, 13 for gravel and 5 for mixed soil.

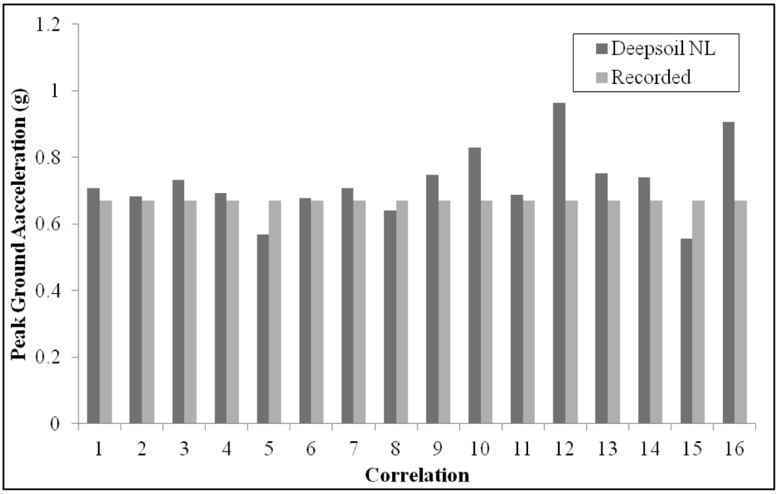

Fig. 7. Comparison of PGA from different G_{max} correlations for sand profile MYG002, M_w 9.0

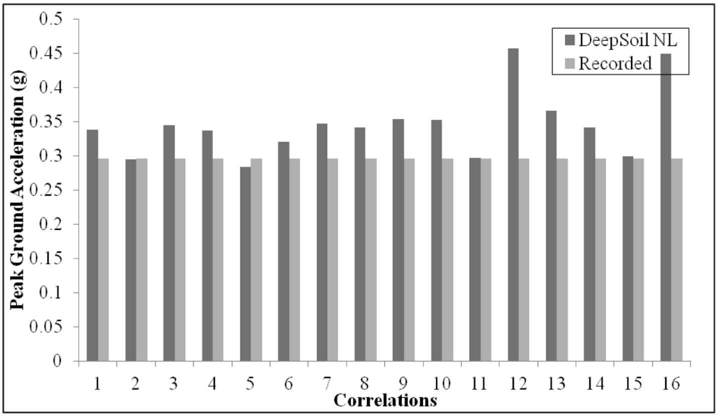

Fig. 8. Comparison of PGA from different G_{max} correlations for clay profile IWT017, M_w 6.8

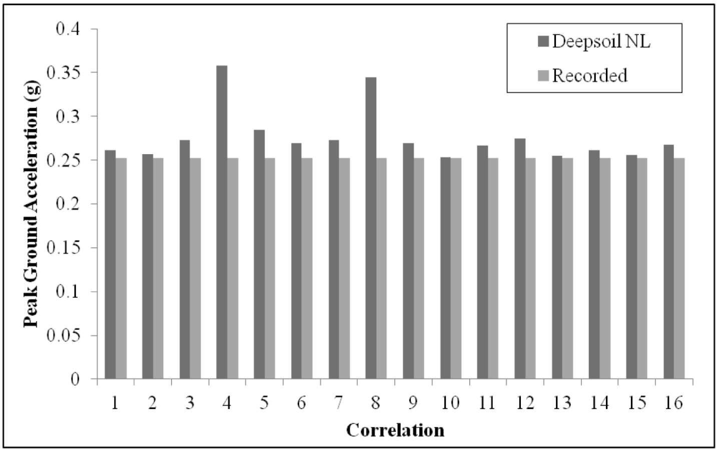

Fig. 9. Comparison of PGA from different G_{max} correlations for gravel profile IWT007, M_w 7.2

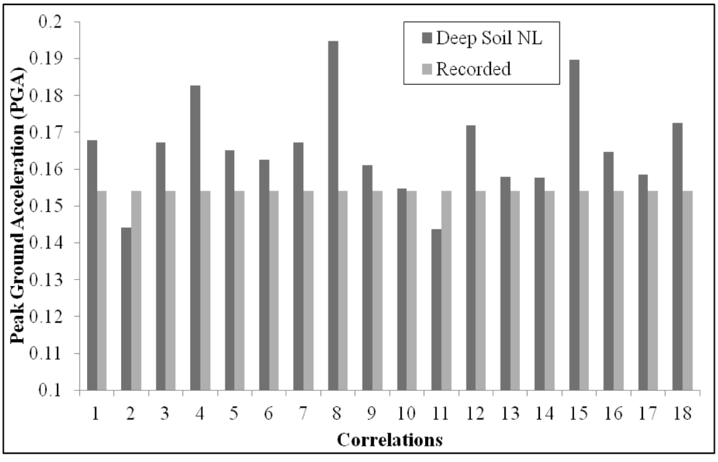

Fig. 10. Comparison of PGA from different G_{max} correlations for mixed soil profile MIE010, Mw 7.4

Table 5. Comparison of peak ground acceleration (PGA) and amplification factor (AF) obtained from different correlation with recorded value

Soil type		**M_w**	**NL analysis by DeepSoil**			
			PGA		**AF**	
			Eq. compared	**Percentage difference**	**Eq. compared**	**Percentage difference**
Sand	MYG002	6.8	12,8,4	±10-20%	12,8,4	±20-30%
		5.1	8,4	> ±50%	8,5	> ±50%
		6.4	12,8,4	±40-50%	12,8,4	±40-50%
		7.0	Except 1,15	±10-20%	Except 1,15	±10-20%
		7.2	12,8,4	±10-20%	12,8,4	±10-20%
		9.0	4,8,2	±0-10%	4,8,2	±0-10%
	EHM006	6.4	12,16,13,10,4	±10-20%	12,16,4,10	±10-20%
	MYG003	7.0	4,8	±30-40%	4,8	±30-40%
		6.4	All eq.	±0-10%	All eq.	±0-10%
		7.2	2,11	±40-50%	2,11	±40-50%
		9.0	4,8	±30-40%	4,8	±30-40%
	MIE008	7.4	2,11,5	±0-10%	11,2,5	±0-10%
	HRS019	6.4	12,5	> ±50%	12,11,5	> ±50%
Clay	FKS008	5.3	5,2,11	> ±50%	5,2,11	> ±50%
		5.4	2,11	> ±50%	2,11	> ±50%
		6.5	14,5,13	> ±50%	14,5,13	±30-40%
		7.2	5,2,11	> ±50%	5,2,11	> ±50%
		9.0	11,5,2	> ±50%	11,5,2	±40-50%
	HRS005	6.4	8,2, 11	> ±50%	11,2, 8	> ±50%
	IWT017	6.8	11,2,5	±0-10%	2,11, 5	±0-10%
		7.2	5, 11	> ±50%	5, 11	> ±50%
		9.0	11,2, 5	±0-10%	11,2, 5	±0-10%
Gravel	EHM002	6.4	4,10	> ±50%	4,10	> ±50%
	IWT023	6.8	16,10	> ±50%	16,10	±40-50%
	NAR004	7.4	15,10,12,13	> ±50%	15,10,12,13	> ±50%
	NAR008	5.5	2,11	±20-30%	2,11	±20-30%
		6.9	2,10,11	> ±50%	2,10,11	> ±50%
	IWT007	7.0	12,10	±20-30%	12,10	±20-30%
		6.4	12,13,15,10	±10-20%	12,13,15,10	±10-20%
		7.2	13,15,10,12	±0-10%	13,15,10,12	±0-10%
		9.0	15,10,13,12	±0-10%	15,10,13,12	±0-10%

Mixed Soil	MIE010	7.4	2,11,5	±0-10%	2,11,5	±0-10%
		6.9	2,11	±20-30%	2,11	±20-30%
	FKS007	5.3	15,5	±40-50%	15,5	±40-50%
		9.0	All Eqs.	±0-10%	All Eqs.	±0-10%
	IWT004	6.8	2,11	±10-20%	2,11	±10-20%
	IWT009	6.8	12,5,2,11	±0-10%	12,5,2,11	±0-10%
		6.1	2,11,5	±10-20%	2,11,5	±10-20%
		6.4	12,4	±10-20%	12,4	±10-20%
		7.2	5,12,2	±10-20%	5,12,2	±10-20%
		9.0	5,2,11	±0-10%	5,2,11	±0-10%
	EHM012	6.4	11,2,5	±40-50%	11,2,5	±40-50%
	MIE011	7.4	11,2, 5	> ±50%	11,2, 5	> ±50%
	EHM009	6.4	Except 2,11,15	±10-20%	Except 11,2,15	±10-20%
	IWT001	6.8	11,2	> ±50%	11,2	> ±50%
		7.2	15,5	> ±50%	15,5	> ±50%
	EHM003	6.4	12,13	±30-40%	12,13,16	±30-40%
	EHM010	6.4	Except 4,15	±10-20%	Except 4,15	±10-20%
	WKY005	5.4	12,16	±10-20%	12,15	±10-20%
		6.9	5, 10	±40-50%	5	±40-50%

SELECTION OF G_{max} CORRELATIONS BASED ON AF

The amplification factor is calculated using PGA values at the surface obtained as a result of the response study with PGA at the rock level as the input. The obtained AF values from DEEPSOIL NL analyses vary from 1 to 5.54 for different correlations. The variation of AF in respect to the recorded value of sand profile MYG002 is shown in Figure 11. It can be observed that for magnitude 9.0 correlations 4, 8 and 2 predict the lowest percentage error of ±0-10%. Observations for different magnitudes can be seen in Table 5. For clay, AF values vary from 1.25 for profile IWT017 to 5.65 for profile HRS005. For profile IWT017, with an earthquake of magnitude 6.8, correlations 2, 5 and 11 predict AF values close to the recorded AF ones (Figure 12). The variation of the amplification factor for gravel varies from 1.55 for profile NAR008 to 5.89 for profile EHM002, for different correlations. For profile IWT007, correlations 10, 15 and 13 predict the least percentage differences in AF for a magnitude 7.2 earthquake (Figure 13). The variation of the amplification factor of mixed soil varies from 0.78 for profile IWT004 to 4.71 for profile MIE011. For profile MIE010, correlations 2 and 11 predict closest to the recorded amplifications for both the magnitudes considered (Figure 14). Similar parametric studies are carried out for all profiles for varying magnitudes and the results are tabulated in Table 5. It can be observed that G_{max} correlation 8 for sand, 2 for clay, 10 for gravel and 11 for mixed soil predict closest to the recorded data for the maximum number of cases for the respective soil column above bedrock. The next closest predictions are derived from G_{max} correlation 12 for sand, 11 for clay, 13 for gravel and 5 for mixed soil.

The shear stiffness of the soil column plays a predominant role in local site effects and, in most cases; the shear modulus of the soil column is estimated using existing G_{max} correlations. In this study, parametric nonlinear site response analysis was carried out considering soil profiles with surface record earthquake data. Sixteen G_{max} correlations were used for arriving at surface response spectral parameters, which were compared with the recorded data. Those G_{max} correlations giving matching spectral parameters are considered as more suitable for the specific soil type. Anbazhagan *et al.* (2015) presented a similar study considering EQL analysis. However, in this study, it is found that the spectral parameters obtained from EQL analysis are higher than those obtained from NL analysis. This difference is due to high-frequency amplification in the NL analysis caused by the instantaneous change in stiffness upon reversal of stress, and the over-damping of high frequencies in EQL analysis at larger strains (Rathje & Kottke, 2011). The significant amplification is due to impedance contrasts between shallow, weak soils and hard rock. Nonetheless, the G_{max} correlations identified in this study are similar to the EQL outcomes. However, the degree of matching in terms of PGA, AF and response spectra is closer in the NL analyses compared to EQL results (refer Table 4). This means that not all the shear modulus correlations available in the literature may be directly applicable to sites, and that appropriate correlations should be selected considering the soil column. Such selection would help in the accurate estimation of representative seismic response parameters.

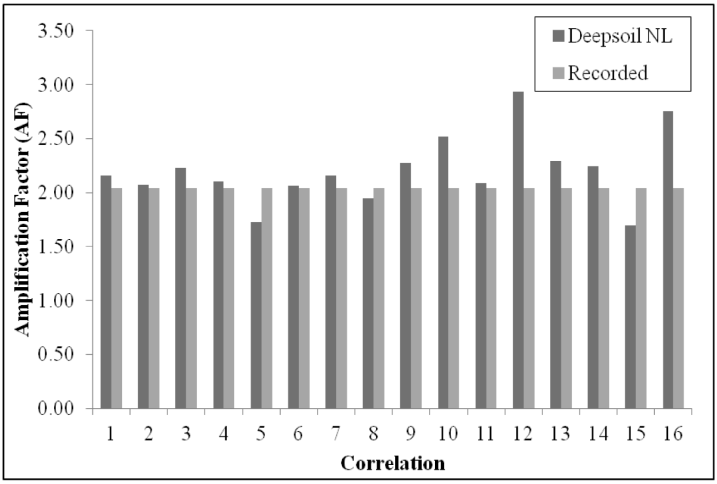

Fig. 11. Comparison of amplification factor from different G_{max} correlations with recorded data AF values sand profile MYG002, M_w 9.0

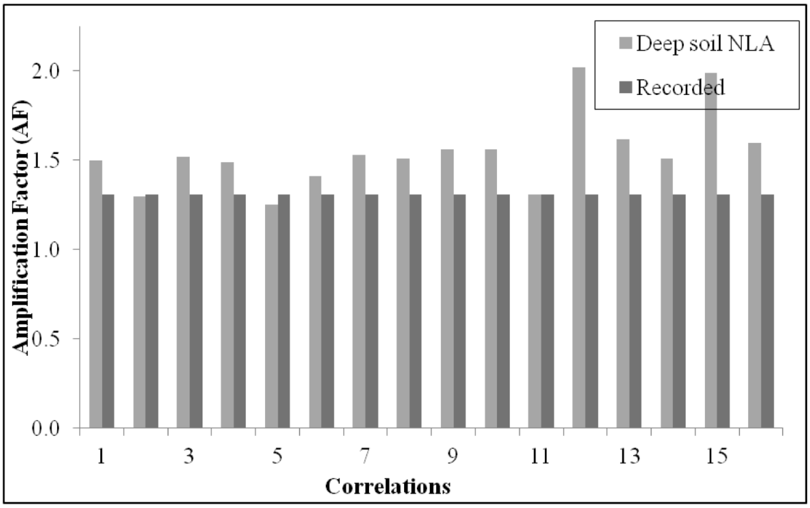

Fig. 12. Comparison of amplification factor from different G_{max} correlations with recorded data AF values clay profile IWT017, M_w 6.8

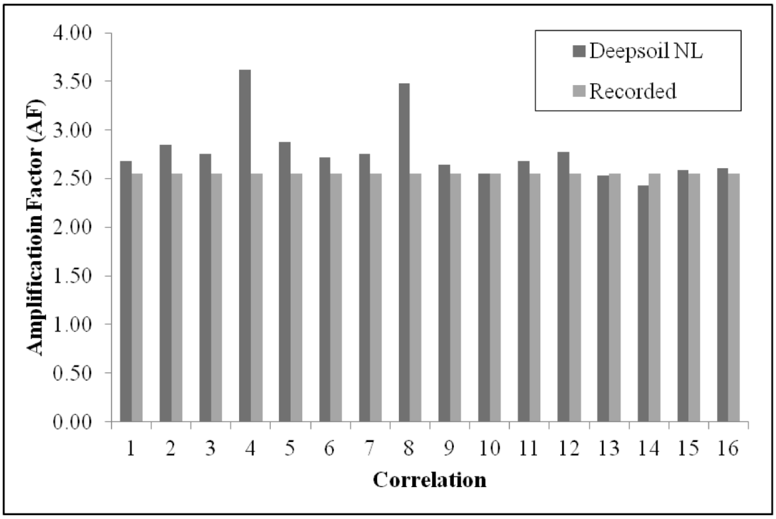

Fig. 13. Comparison of amplification factor from different G_{max} correlations with recorded data AF values gravel profile IWT007, M_w 7.2

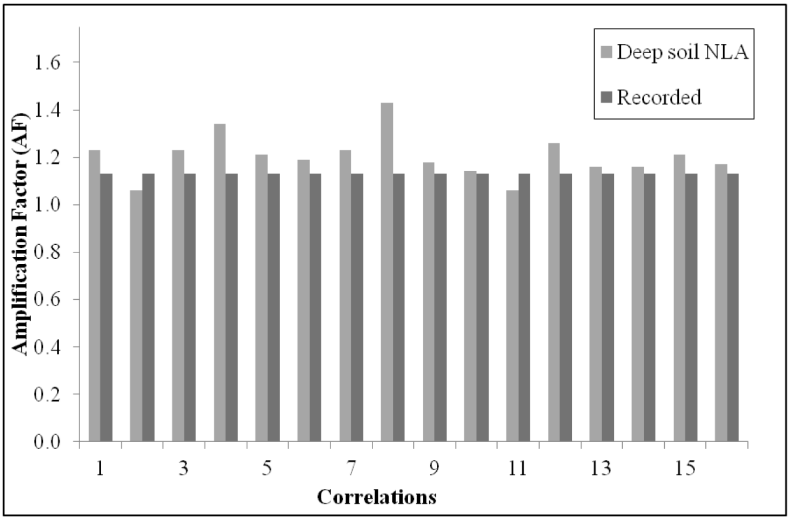

Fig. 14. Comparison of amplification factor from different G_{max} correlations with recorded data AF values mixed soil MIE010, M_w 7.4

CONCLUSIONS

Many shear modulus correlations with SPT N-values have been developed for different soil types following certain assumption. However, among these, just a few G_{max} correlations have been repeatedly used to carry out site response analyses, irrespective of soil type. In this study, an attempt has been made to present suitable shear modulus and SPT correlations for different soil columns by carrying out a detailed site response study of sites with recorded ground motion data and SPT N-values. Initially, the response study was carried out using both EQL and NL models, but it was found that the EQL results were much higher than the NL results. Nonlinear site response studies using DEEPSOIL for the soil profiles were therefore used to derive the final conclusions. The obtained results were compared with the surface record of the same earthquake event, in terms of PGA, AF and response spectra. This study shows that the response studies carried out by using a few repeated correlations (which are inbuilt in response analysis software) will tend to result in over-prediction of response parameters for different soil column types. In fact, the PGA, response spectrum and AF values obtained from only a few shear modulus correlations are comparable with the respective recorded data. G_{max} correlation 8, proposed by Ohsaki & Iwasaki (1973), can be used for the best prediction of surface response parameters in sand and a mixture of sand with sandy soil column sites, with different site classes and overburden thickness. Other than correlation 8, correlation 12, proposed by Imai & Tonouchi (1982) also predicts response parameters that match closely with recorded values for sand soil columns. Even though all the correlations predict higher amplifications than the recorded values for clay, G_{max} correlation 2, proposed by Ohba & Toriumi (1970), has the least percentage of error and also better matches the average spectra for sites having clay soil columns. Correlation 11, proposed by Imai & Tonouchi (1982), is the next best match for the prediction of response parameters in clay soil columns. G_{max} correlation 10, proposed by Imai & Tonouchi (1982), has the least percentage error and a better match of the average spectra than other correlations for sites with gravel soil columns. For sites with a mixture of clay and sand, correlation 11, proposed by Imai & Tonouchi (1982), predicts well for different overburden thicknesses and magnitudes. For profiles with clay in-between gravely soils, correlation 5, proposed by Ohasaki & Iwasaki (1973), predicts best, while correlation 15, proposed by Anbazhagan & Sitharam (2010), exhibits the least percentage of error for soil columns, which are a mixture of gravel, sand and fill soil for different magnitudes. The above correlations are recommended for the estimation of shear modulus for representative site response studies using SPT N-values in the absence of shear wave velocity measurement. The results obtained from this study are useful for site response studies of sites, where site specific shear modulus and N correlation is not available and only SPT N with soil type data are available.

ACKNOWLEDGEMENTS

The authors wish to thank the Kyoshin Net Strong Motion Network of Japan for providing an excellent earthquake database and valuable feedback for conducting this research. Authors thank SHAKE Team and Gustavo Ordonez for providing separate menu options for this study in SHAKE2000 programme. The authors extend their sincere appreciation to the Deanship of Scientific Research at King Saud University for its funding for this Prolific Research Group (**PRG-1436-06**).

REFERENCES

Adams, J. 2007. Soil amplification in Ottawa from urban strong ground motion records. Proceeding to the Ninth Canadian conference on earthquake engineering, Ottawa. Canada.

Anbazhagan, P., Aditya, P. & Rashmi, H.N. 2012. Review of correlations between SPT N and shear modulus: A new correlation applicable to any region. Soil Dynamics and Earthquake Engineering, **36**:52-69.

Anbazhagan, P., Neaz Sheikh, M. & Aditya, P. 2013. Influence of rock depth on seismic site classification for shallow bedrock regions. Natural Hazard Review ASCE, **14**(2):108-121.

Anbazhagan, P., Manohar, D.R., Sayed, S.R., Moustafa. & Nassir, S. Al-Arifi. 2015. Effect of Shear Modulus Correlation on Site Response Study. Disaster Advances, **8**(2):16-30.

Anbazhagan, P. & Sitharam, T.G. 2010. Relationship between low strain shear modulus and standard penetration test 'N' values. ASTM Geotechnical Testing Journal, **33**(2):150-164.

Chen, W.F. & Scawthorn, C. 2003. Earthquake Engineering Handbook. New York, U.S.A, CRC Press.

Crow, H., Hunter, J.A., Pugin, A., Gooks, G., Motasedian, D. & Khasheshi-Banab, K. 2007. Shear wave measurements for earthquake response evaluation in Orleans, Ontario. Proceedings of the 60th Canadian Geotechnical Conference, Ottawa, Cannada. 2:871-879.

Hara, A., Ohta, T., Niwa, M., Tanaka, S. & Banno, T. 1974. Shear modulus and shear strength of cohesive soils. Soils and Foundations, 14:1-12.

Hashash, Y.M.A., Groholski, D.R., Phillips, C.A., Park, D. & Musgrove, M. 2012. DEEPSOIL 5.1, User Manual and Tutorial, Pp. 107.

Hwang, H.H.M. & Lee, C.S. 1991. Parametric study of site response analysis. Soil Dynamics and Earthquake Engineering, **10**(6):282-290.

Imai, T. & Yoshimura, Y. 1970. Elastic wave velocity and soil properties in soft soil (in Japanese) Tsuchito-Kiso, **18**(1):17-22.

Imai, T. & Tonouchi, K. 1982. Correlation of N-value with S-wave velocity and shear modulus. In: Proceedings of the 2nd European Symposium on penetration testing. Pp. 57–72.

Kramer, S.L. 1996. Geotechnical Earthquake Engineering. Published by Pearson Education Ptd. Ltd, Reprinted 2003, Delhi, India.

Kyoshin Net (K-Net) Strong Motion Database. National Research Institute for Earth Science and Disaster Prevention. Ibaraki-Kenn, Japan, (http://www. K-net.bosai.go.jp).

Marano, K.D., Wald, D.J. & Allen, T.L. 2010. Global earthquake casualties due to secondary effects: a quantitative analysis for improving rapid loss analyses. Natural Hazards, 52:319-328.

Matasovic, Neven. & Vucetic, M. 1993. Cyclic Characterization of Liquefiable Sand. ASCE Journal of Geotechnical and Geoenvironmental Engineering, **119**(11):1805-1822.

Ohba, S. & Toriumi, I. 1970. Research on vibration characteristics of soil deposits in Osaka, part 2, on velocities of wave propagation and predominant periods of soil deposits. Abstract, Technical meeting of Architectural Institute of Japan [in Japanese].

Ohta, T., Hara, A., Niwa, M. & Sakano, T. 1972. Elastic moduli of soil deposits estimated by N-values. In: Proceedings of the 7th annual conference. The Japanese Society of Soil Mechanics and Foundation Engineering. Pp. 265–8.

Ohsaki, Y. & Iwasaki, R. 1973. Dynamic shear moduli and Poisson's ratio of soil deposits. Soils and Foundations, **13**(4):61-73.

Ohta, Y. & Goto, N. 1976. Estimation of S-wave velocity in terms of characteristic indices of soil. Butsuri-Tanko, **29**(4):34-41.

Rathje, E.M. & Kottke, A.R. 2011. Relative differences between equivalent linear and nonlinear site response methods. Paper presented at the 5th International conference on earthquake geotechnical engineering, Santiago, Chile.

Schnabel, P.B., Lysmer, J. & Seed, H. Bolton. 1972. SHAKE: A Computer Program for Earthquake Response Analysis of Horizontally Layered Sites. Earthquake Engineering Research Center, University of California, Berkeley:Report No. UCB/EERC-72/12: 102.

Schnabel, P.B. 1973. Effects of Local Geology and Distance from Source on Earthquake Ground Motion, Ph.D. Thesis, University of California, Berkeley, California.

Seed, H.B. & Idriss, I.M. 1970. Soil Moduli and Damping Factors for Dynamic Response Analyses. Earthquake Engineering Research Center, University of California, Berkeley, California, Rep. No. EERC-70/10.

Seed, H.B., Idriss, I.M. & Arango, I. 1983. Evaluation of liquefaction potential using field performance data. Journal of Geotechnical Engineering, **109**(3):458-482.

Seed, H.B., Wong, R., Idriss, I.M. & Tokimatsu, K. 1986. Moduli and damping factors for dynamic analyses of cohesionless soils. Journal of Geotechnical Engineering, ASCE. **112**(11):1016-1032.

SHAKE2000. 2009. A computer program for the 1-D Analysis of Geotechnical Earthquake Engineering Program. Users Manual, Pp. 258.

Vucetic, M. & Dobry, R. 1991. Effect of soil plasticity on cyclic response. Journal of Geotechnical Engineering, ASCE. **117**(1):89-107.

Submitted: 16/06/2015

Revised: 24/11/2015

Accepted: 05/01/2016