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Empirical correlations for strain dependent linear 1D ground response analysis for Guwahati, India based on detailed analyses

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ABSTRACT: Ground response analysis (GRA) received considerable attention due to increased seismic activity worldwide. While dynamic soil properties curves (DSPC) is pre-requisite for GRA, these are not readily available on site/region specific level. Outcomes from GRA, based on DSRC developed for other parts of globe, is debatable to be considered as regional characteristics. In this work, two correlations are proposed which determine γ for a known peak horizontal acceleration (PHA) and depth (H) from ground surface based on 300 GRA analyses for Guwahati, India. Based on above correlations, once γ at a particular H and for a PHA is known, linear GRA based on set of shear modulus (G) and damping ratio (β) corresponding to this γ, can give comparable results of Equivalent linear GRA (ELGRA) up to 0.5% (γ). However, this way entire DSRC of subsoil will not be required for GRA.

1 INTRODUCTION

Earthquakes (EQs) and its related damages are function of the shaking intensity at the ground surface level. The bedrock level shaking can be determined in the form of peak horizontal acceleration (PHA) by performing a detailed seismic hazard analysis. However, when an EQ wave travels from bedrock towards ground surface, the properties of the bedrock motion get significantly altered due to interaction with each subsoil layer. Such modifications in bedrock motion properties can be observed in terms of amplitude, frequency content and duration. These modifications in ground motion properties are termed as local site effects (LSE). In order to estimate surface level shaking (peak ground acceleration or PGA), quantification of local site effect (LSE) is necessary. LSE can be estimated by performing a ground response analysis (GRA). Though there are several methods of GRA (linear, equivalent linear and non-linear) available, equivalent linear method of GRA (ELGRA) is most commonly practiced for its simplicity and reasonable accuracy. Input parameters in ELGRA are bedrock level motion, soil stratification and their in-situ dynamic soil properties curves (DSPC). In the absence of regional level EQ records, EQ records compatible with regional seismic hazard are usually chosen for GRA. In addition, existing EQ records are scaled to match with the regional seismic hazard and are then utilized in GRA. Synthetic ground motions have also been employed for the purpose.

DSPC on the other hand, are however also not available for most of the sites. Thus, DSPC which were developed for other regions are used frequently by researchers while performing ELGRA. DSPC comprises of shear modulus degradation (G/G_{max}) curve and damping ratio (β) curves. These curves are basically the representation of change in shear modulus (G) and β values with developed shear strain level (γ) in each soil layer. In ELGRA, initially the soil layers are modelled with low strain G and β which are later updated based on compatible γ in an iterative procedure till assumed G and β matches with DSPC based γ.

However, if the above developed γ during a probable EQ can be estimated in advance, then GRA based on only one set of G and β values will be sufficient enough to understand LSE. This way, the limitation of the absence of regional DSPC can be avoided, which is the objective of present work. It is achieved based on 10 boreholes from Guwahati city (India) drilled along the GS road (Guwahati-Shillong road) following 300 ELGRA. Detailed discussion is as follows.

2 STUDY AREA & SEISMICITY

Guwahati, a major city in the north-east India is located between 26.08°N-26.25° N and 91.58°E – 91.92°E, covers an area of around 600 sq. km (Raghukanth et al. 2011). It is located towards the southeastern part of Kamrup district and is built on soft alluvium deposit transported by the river Brahmaputra. Guwahati is considered the gateway to northeast India as it connects all other cities of northeast India. Indian government is planning to develop Guwahati as a smart city along with 58 other cities of India. As a result, there will be rapid infrastructure development in the coming years. According to census report 2011, Guwahati has a population of 1 million, which is increasing at a much faster rate. Seismicity wise, Guwahati city falls in zone V of the seismic hazard zonation map (BIS 2002) of India, the highest seismicity zone of the country. This can be understood from the fact that Guwahati is surrounded by Himalayan collision zone from the north and northeast, Indo-Mayanmar subduction interface from the east and the Meghalaya plateau-Mikir tectonic block from the south. In the last 110 years, the 20 major EQs and 2 great EQs have caused minor to major damages/induced effects in Guwahati (Kayal et al. 2006). The 1897 great Assam EQ (M_w 8.1) was originated in the Dhudnoi/Chedrang fault. During this EQ, an area of 1, 50, 000 square mile was badly affected (Oldham 1899). Ground shaking was felt all over the Guwahati city. The Kamakhya temple and many stone made bridges in Guwahati city were severely damaged (Rajendran et al. 2004). The NW-SE trending Kopili fault generated the 1869 Cachar EQ and the 1943 EQ, both having magnitude greater than 7.0 in moment magnitude scale. During the 1869 Cachar EQ, several building damages were encountered at Pan Bazar area in Guwahati. In addition, it is reported by CNDM (2002) that during the 1969 Cachar EQ, at many places in Guwahati, water table rose to the ground surface suggesting a strong case of liquefaction. The Jamuna/Dhubri fault was responsible for the 1931 Dhubri EQ (M_w 7.1). In addition to regional seismicity around Guwahati, several faults are also located within the city. These include 1) a 5 km long faults running between Nilachal and fatasil hill, 2) 10 km long fault between Kalapahar and Fatasil hil, 3) 20 km long fault between southern foothills and river Brahmaputra and 4) a fault running between the southern foothills and the Kalapahar-fatasil hill range (GSI 2000, Raghukanth & Das 2009 & Kumar et al. 2014). Above discussion clearly highlights that the seismic activity of Guwahati is controlled by regional as well as local faults. Similarly, in the light of past damages witnessed during various events, chances of similar damage during future EQs cannot be avoided. Further, presence of local soil will alter the ground motion scenario for Guwahati.

3 LITHOLOGY

As per Guwahati Metropolitan Development Authority (GMDA 2016), bedrock medium of Guwahati city is dominated by the Precambrian Gneissic complex with a hint of porphyritic granites at several places. The gneissic basement composed of granite gneiss, biotite gneiss, biotitic schist and quartzite Quaternary alluvium. Further, the alluvium fills over the gneissic complex consists of alternate beds of unconsolidated sand, silt and clay. Presence of minerals such as quartz, biotite, muscovite along with typical Brahmaputra sand are found at many places such as Bharalumukh, Machkhowa, Chatribari and Ulubari (GMDA 2016). As per Kumar et al., (2018), subsoil in Guwahati consists of alternate layers of sand, clay and silt till 30m depth. For the present work, 10 boreholes (referring to Kumar et al. 2018), that were drilled for Mass Rapid Transit System (MRTS) project are collected from GMDA. All the boreholes were drilled up to 30m depth from the ground surface. SPT test was conducted at every 3m interval and depths where strata encountered a change. Both disturbed and undisturbed samples were collected by means of standard split spoon sampler and thin walled samplers respectively. Further, the samples were tested in laboratory to obtain necessary geotechnical properties (GMDA 2016). One typical borelog is shown in Table 1. It can be observed from the Table 1 that the subsoil lithology for the concerned area (Guwahati-Shillong road) consists of mainly clay layers with intermediate to high compressibility and silty sand layers. Similar types of soil were also reported by Raghukanth et al. (2011) for Guwahati city. Similar observations can also be made from other 9 borelogs. Collectively based on 10 borelogs, it can be concluded that, soft soil (SPT-N<15, according to National Earthquake Hazard Reduction Program (NEHRP & BSSC 2003) is present up to a depth of 10 m. Stiff soil (15<SPT-N<50, NEHRP) is found between 10 m depth and approximately 15 m depth and after that hard soil (SPT-N>50, NEHRP) is encountered. Depth of water table in these boreholes were reported to vary from 2m to 6.7m after 24 hours of observation.

4 SELECTION OF INPUT MOTION

In GRA, an important input parameter is bedrock motion. It has to be highlighted that once the bedrock motion is known; it can be used for quantification of induced effects as well as to understand the role of local soil during bedrock motion corresponding EQ scenario. However, most of the times, sufficient regionally recorded ground motions for the site where GRA is being carried out, are not available. In such situations, ground motions recorded at other parts of the worlds are commonly employed. Standard ground motions during 1940 El-Centro EQ, 1985 Mexico EQ, 1989 Loma Prieta EQ, 1994 Northridge EQ, 1995 Kobe EQ, 1999 Chi-Chi EQ etc. have been frequently used by researchers all over the world including India (Phanikanth et al. 2011 & Kumar et al. 2016). Often above recorded ground motions are scaled up

Table 1. Borelog (GMDA 2016)

Bore hole No. C4/8		GWT at 6.60m		Samples			
Depth (m)	Description	Soil classification	Thickness	Type	No	Depth (m)	SPT-N
0	Filled up materials with garbages & blackish sandy soil	SP	4.5	DS	1	1	
				UDS	1	1.5	
				SPT	1	3	4
4.5				UDS	2	4.5	
15	Blackish silty clay	CH/CI	10.5	SPT	2	6	5
				UDS	3	7.5	
				SPT	3	9	9
				UDS	4	10.5	
				SPT	4	12	12
				UDS	5	13.5	
				SPT	5	15	13
21	Grayish clay	CH	6	UDS	6	16.5	
				SPT	6	18	26
				UDS	7	19.5	
				SPT	7	21	36
24	Blackish silty clay	CH	3	UDS	8	22.5	
				SPT	8	24	70
30	Brownish coarse sand	SM	6	UDS	9	25.5	
				SPT	9	27	R
				UDS	10	28.5	
				SPT	10	30	R

to comply with the response spectrum of the concerned site. Researchers even tried to generate synthetic ground motions in accordance with uniform hazard spectra and seismic hazard value at the site (Kennedy et al. 1984, Deodatis 1996 & Bazzurro et al 1998).

If GRA is performed utilizing ground motions which are recorded elsewhere, then the regional seismicity is completely ignored. Similarly, use of synthetic ground motions and a few regionally recorded motions which are in accordance with the local seismicity may not be justified here, since one or two motions do not represent all the uncertainties related to ground motion characteristics of future EQs. Therefore, selection of a large set of ground motions is advisable (Kumar et al. 2016). Kumar et al. (2016) further emphasized that the selected motions should be rich in terms of variations in ground motion characteristics namely, amplitude, frequency content and duration. Apart from this, selected motions should include both near field and distant recorded motions to account for the effect of epicentral distance (Kumar et al. 2016). Considering the above factors, Kumar et al (2016) shortlisted 30 ground motions from PEER (Pacific Earthquake Engineering Research) database which were used for GRA of Delhi region. The same set of 30 motions are used in this study as well. The details of the ground motions are shown in Table 2.

Table 2. Input motion details (As per Kumar et al 2016)

Sr. No.	Ground Motion Details as per SHAKE2000	Epicentral Distance (Km)	Magnitude	PGA (g)	Duration (s)	Predominant Frequency (Hz)
1	ADAK, ALASKA 1971-M 6.8;R-67KM, N81E	86.77	6.8	0.098	24.58	3.32
2	ANCHORAGE, ALASKA 1875, M-6, R81-GOULE HALL STATION	81.93	6	0.036	18.59	5.42
3	ANCHORAGE ALASKA 1975, M 6, R 79, WESTWARD HOTEL STATION (BASEMENT)	78.37	6	0.049	38.96	1
4	ANZA 02/25/80, BORREGO AIR BRANCH 225	43.1	5.3	0.046	10.25	2.39
5	ANZA 02/25/80 1047, TERWILLIGER VALLEY 135	15.8	5.3	0.08	10.01	6.54
6	BISHOP-ROUND VALLEY 11/23/84 1914, MCGEE CREEK SURFACE 270	42.35	5.8	0.075	6.8	3.9
7	BORREGO MOUNTAIN 04/09/68 0230, EL CENTRO ARRAY 9, 270	60	6.4	0.056	39.95	0.46
8	BORREGO MOUNTAIN 04/09/68 0230, PASADENA-ATHENAEUM, 270	216.8	6.4	0.009	60.23	0.61
9	BORREGO MOUNTAIN 04/09/68 0230, TERMINAL ISLAND, 339	205	6.4	0.008	51.8	2.5
10	CAPE MENDOCINO EARTHQUAKE RECORD 04/25/92, MW-7.0, 90 DEG COMPONENT	10	7.1	1.03	59.98	4.44
11	CHALFANT 07/20/86 1429, BISHOP PARADISE LODGE,070	19.8	6.4	0.046	39.95	16.5
12	CHILE EARTHQUAKE, VALPARAISO RECORD, 3/3/85	129.2	7.8	0.12	79.39	2.1
13	COALINGA 05/02/83 2342 PARKFIELD, FAULT ZONE 6/090	43.9	6.5	0.055	39.95	0.43

(*Continued*)

Table 2. (*Continued*)

Sr. No.	Ground Motion Details as per SHAKE2000	Epicentral Distance (Km)	Magnitude	PGA (g)	Duration (s)	Predominant Frequency (Hz)
14	COALINGA 05/09/83 PALMER AVE ANTICLINE RIDGE, 090	12.5	5.3	0.215	40	2.29
15	GEORGIA, USSR 06/15/91 0059, BAZ X	49	6.2	0.033	34.07	1.22
16	IMPERIAL VALLEY 10/15/79 2319, BONDS CORNER 230	15.9	5	0.1	19.88	1.41
17	KERN COUNTY 7/21/52 11:53, SANTA BARBARA COURTHOUSE 042	80.5	7.5	0.086	75.35	1.84
18	KOBE 01/16/95 2046, ABENO 000	24.9	6.9	0.22	139.98	0.26
19	KOBE 01/16/95 2046, KAKOGAWA 000	22.5	6.9	0.25	40.91	0.91
20	KOBE 01/16/95, KOBE PORT ISLAND 090	0.9	6.9	0.53	42	0.79
21	LIVERMORE 01/27/80 0233, HAYWARD CSUH STADIUM 236	33.9	5.8	0.027	15.98	3.61
22	LIVERMORE 01/27/80 0233 LIVERMORE MORGAN TERR PARK 265	20.6	5.8	0.197	24	5.61
23	LOMA PRIETA TA 10/18/89 00:05, ANDERSON DAN DOWNSTREAM 270	16.9	7	0.24	39.59	2.14
24	LOMA PRIETA TA 10/18/89 00:05, HOLLISTER DIFF ARRAY 255	13.9	7	0.27	40	1.48
25	MICHIOACAN EARTHQUAKE 19/9/85, CALETA DE CAMPOS, N-COMPONENT	38.36	8.1	0.14	81.06	1.39
26	NORTHERN CALIFORNIA 09/22/52 1141, FERNDALE 134	44.3	5.2	0.07	40	1.31
27	NORTHRIDGE EQ 1/17/94 1231, ANACAPA ISLAND	71.4	6.7	0.013	40	4.46
28	NORTHRIDGE EQ 1/17/94 1231, ARLETA 360	9.5	6.7	0.31	39.94	1.46
29	PARKFIELD 06/28/66 04:26, CHROME # 8	11.2	6.1	0.116	26.09	0.85
30	TRINIDAD 11/08/08, 10:27, RIO DEL OVERPASS E	72	7.2	0.13	22	3.14

5 1D SOIL MODEL

Soil behavior is very complex when subjected to an EQ excitation. As the γ value increases in a soil deposit, the G and β values are reduced and increased respectively, controlling accordingly the soil response. These change in G and β values with respect to γ are represented by DSPC and can be obtained by detailed laboratory experiments. However, due to limited availability of regional DSPC, standard DSPC developed for other regions are being utilized in most of the GRA performed across the world (Stewart et al. 2001). These DSPC are different for different type of soils. Thus, while performing a GRA, DSPC are chosen based on a number of factors such as soil type, confinement, plasticity index, OCR etc. For the present work, 4 types of soils (SM, CH, CI and CL) are encountered as observed from the 10 boreholes. The silty sand (SM) layers are modelled with DSPC developed by Seed & Idriss (1970) for average sand. Similarly, G/G_{max} curves for clay layers are chosen from the curves developed by Sun et al. (1988). Sun et al. (1988) studied the effect of PI and OCR on modulus degradation behavior of clay type of soil and proposed a number of G/G_{max} curves for different PI range. Hence, the clay layers (CH, CI, CL) are modelled accordingly with different G/G_{max} curves proposed by Sun et al. (1988). According to Seed & Idriss (1970), damping curves for clay soils are independent of PI of the soil. Thus, the clay layers are modelled with average damping curve proposed by Seed & Idriss (1970) for clay soil. Further, DSPC developed by Schnabel (1973) for rock are used to model the very stiff medium (N≥50).

In ELGRA, initial low strain value of G and β for each of the layers are considered and then these get updated in an iterative manner till matching with corresponding γ as indicated by DSPC. Therefore, initial low strain G (G_{max}) and β values are required as input. For the purpose β values are considered to be 5% for all the layers. G_{max} values for different layers are computed from the recorded SPT-N values, based on an empirical correlation (V_s=46.56$N^{o.62}$) developed by Kumar et al. (2018) for the Guwahati region.

6 ANALYSES

For the present work, two sets of analyses are carried out. At first, ELGRA are performed with the earlier mentioned dynamic soil properties. All of these analyses are performed using the MATLAB code for ELGRA developed by Kumar & Mondal (2017). Soil layers in this MATLAB code are modelled as per the data obtained from the boreholes. Data from all the 10 boreholes are considered for the analyses and each of the 30 input motions are assigned at the bottom of each of the 10 boreholes. Thus, a total 300 number of analyses are carried out and results are obtained in terms of γ time history at the interface of different soil layers. From these γ time histories, the peak γ values are recorded for each of the soil layers. This peak γ depends on several factors such as soil type, PHA and depth of layer from ground surface (H). For the current work, the variations of γ with H and for different PHA values are studied for sand and clay separately as can be observed from Figure 1. It can be observed from Figure 1 that with increase in depth, the value of γ is increasing with PHA for sand as well as clay. Further, a two-step regression analysis as per Kumar et al (2017) is performed to come up with two correlations (Eq. 1, Eq. 2) which narrates the dependency of γ on embedment depth (H) and input PGA.

$$\gamma = \left(-0.0006H^2 + 0.0284H - 0.0269\right) \times PHA^{\left(0.6943H^{0.1156}\right)} \quad \text{(For Clay)} \tag{1}$$

$$\gamma = (-0.0002H^2 + 0.0184H + 0.0239) \times PHA^{(-0.0002H^2+0.0131H+0.8778)} \quad \text{(For Sand)} \tag{2}$$

In the second set of analyses, which is done to explain the proposed methodology, three ELGRA are performed on a different boreholes which is located in the vicinity of the above considered 10 boreholes location. These second set of analyses are carried out using motions 5, 7 and 20 as summarized in Table 2. The borehole is modeled with the earlier mentioned

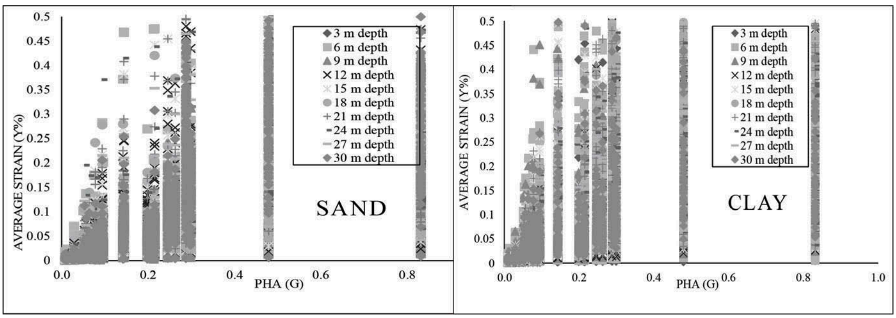

Figure 1. Variation of strain with depth

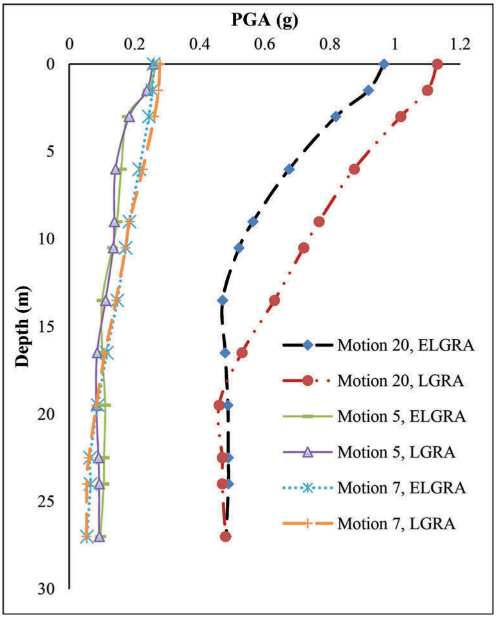

Figure 2. PGA variation with depth based on LGRA (considering 5% damping) and ELGRA for a typical borehole

DSPC for sand and clay type of soils. (Table 1). Outcomes in the form of PGA variation with depth are observed for each of these three motions. Further, the same borehole data and motions are utilized to perform linear ground response analysis (LGRA). In LGRA, the input G values for different layers are computed based on the empirical correlation developed by Kumar et al (2018) as highlighted earlier and the β values for all the layers are kept as 5%. From the LGRA, PGA variation with depth for ground motions 5, 7 and 20 are estimated and compared with those obtained from ELGRA (Figure 2).

7 RESULTS AND DISCUSSION

From Figure 2, it can be observed that both LGRA and ELGRA yield similar results for motion 5 and 7. The PGA variation along with depth for motion 5 and 7 obtained are matching very well. It should be highlighted here motion 5 and 7 have bedrock PHA values of 0.08g and 0.056g respectively. At these low PHA, soil is expected to experience low γ and consequently show limited non-linearity in its stress-strain behavior. In order to justify the above statement, the γ values are computed at different depths for both clay and sand by utilizing appropriate correlation developed in this work. It is observed that the γ values estimated in the clay and sand layers are below 0.02%. At this low γ, soil behaves like elastic material. Therefore, LGRA is perfectly applicable for these type of low γ conditions. However, as per Figure 2, slight differences can be observed between the results obtained from ELGRA and LGRA for motion 20. It has to be highlighted that motion 20 has approximately 10 times higher PHA (0.53g) in comparison to motion 5 and 7. Thus, higher PHA will result in higher γ. Therefore, comparatively higher non-linearity can be expected from soil. Development of higher γ for motion 20 has been further confirmed when the γ values, computed from the developed correlations for specific type of soils are considered. The γ for motion 20 varies from 0.015%-0.2% as per the developed correlations. Since, G and D values at this high γ are not readily available for the concerned region, low strain G_{max} and β values have been considered for the analysis.

8 CONCLUSIONS

In the present work, highlighting the limitation in modelling LSE on regional scale due to unavailability of DSPC, two empirical correlations are proposed for sand and clay each for Guwahati. Proposed correlations are based on 300 ELGRA done on 10 boreholes from Guwahati and using 30 input motions on each borehole. Developed correlations determine the value of γ which is going to be developed in a soil layer corresponding to known bedrock level PHA and depth (H) below ground surface. In case, $\gamma \leq 0.2\%$, rather going for DSPC developed for other regions for LSE determination, in-situ field test based soil properties can give relatively accurate results using LGRA.

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