1D nonlinear GRA for assessing the liquefaction susceptibility of a typical subsurface profile at Agartala city

1D GRA non-linéaire pour évaluer la susceptibilité de liquéfaction d'un profil typique de subsurface de la ville d′Agartala

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ABSTRACT: Ground Response Analysis (GRA) forms an integral part of geotechnical earthquake engineering as it helps to identify the amplification/attenuation of a strong motion at a site and also compute the surface accelerations. This paper reports about the outcome of a one-dimensional nonlinear GRA (incorporating Non-Masing rules) study, conducted for a typical soil stratigraphy of Agartala city, situated in North-Eastern part of India. Conducting GRA study for this region is extremely necessary as it is located in a zone having the highest level of seismic hazard potential in the country. The central part of Agartala consists of soft-to-loose layered alluvial deposits, formed by the sedimentations from River Haora. Recorded and scaled-up motion components of the Sikkim earthquake are used as input motions for the analyses. Based on the GRA results, a liquefaction susceptibility analysis is also performed which clearly indicates that the top soil within a depth of 0-12 m is a potentially liquefiable stratum. The depth and extent of the zone of liquefaction is found to increase substantially with the increase in the peak acceleration of the input motion. The results presented in the form of GRA and liquefaction potential parameters for the site gives significant input pertaining to sustainable design of future structures and retrofitting the existing ones in order to reduce the seismic vulnerability of Agartala city.

Résumé : L'analyse de réponse des sols (GRA) fait partie intégrante de l'ingénierie géotechnique des tremblements de terre, car elle aide à identifier l'amplification / atténuation d'un fort mouvement sur un site et à calculer les accélérations de surface. Cet article décrit les résultats d'une étude unidimensionnelle non-linéaire de GRA (intégrant les règles de non-Masing), réalisée pour une stratigraphie typique du sol de la ville d'Agartala, située dans le nord-est de l'Inde. Faire une étude GRA pour cette région est extrêmement nécessaire, puisqu'elle est située dans une zone présentant le plus haut niveau de risque sismique potentiel dans le pays. La partie centrale d′Agartala est constituée de dépôts alluviaux superposés mous à lâches, formés par les sédimentations de la rivière Haora. Les composantes de mouvement enregistrées et accrues du séisme au Sikkim sont utilisées comme mouvements d'entrée pour les analyses. Sur la base des résultats du GRA, une analyse de sensibilité à la liquéfaction est également effectuée, ce qui indique clairement que le sol supérieur à une profondeur de 0-12 m est une couche potentiellement liquéfiable. On constate que la profondeur et l'étendue de la zone de liquéfaction augmentent sensiblement avec l'augmentation de l'accélération maximale du mouvement d'entrée. Les résultats présentés sous forme de GRA et les paramètres potentiels de liquéfaction pour le site apportent une contribution significative à une conception durable des futures structures et à la réhabilitation des structures existantes, afin de réduire la vulnérabilité sismique de la ville d'Agartala.

KEYWORDS: Ground Response Analysis, Nonlinear, Non-Masing, Liquefaction

1 INTRODUCTION

The devastating effects of earthquake motions on structures and foundation systems are mainly governed by the response of soil subjected to seismic shaking. The stress-strain behaviour of soil, strength characteristics and soil properties govern the soil response during seismic wave propagation. The soil response can be represented based on parameters such as peak horizontal acceleraton (PHA), shear strain, spectral acceleration. These response parameters serve as guidelines for seismic design of foundations and structures. Thus, conducting a detailed GRA study is of utmost importance to characterize any site.

Agartala, the capital and the largest city of state Tripura, is highly vulnerable to earthquakes and it is designated as seismic zone V as per IS: 1893-I (2002). According to the records of Indian Meteorological Department, about 41 earthquakes of magnitude 5.6 and greater have occurred in Tripura during the period from 1970 to 2000. This paper focusses on a non-Masing criteria based nonlinear 1D GRA carried out using DEEPSOIL v6.0 and liquefaction potential assessment of a soil profile in Agartala.

In nonlinear GRA approach, the soil profile is converted into a mass-spring-dashpot system using multi-degree-of-freedom lumped parameter model. The dynamic equation of motion (Eq. 1) is solved at each time step using numerical integration to analyze the soil response. Numerical integration technique such as Newmark β method (Newmark 1959) may be used. Any non-linear stress-strain model, following Masing or non-Masing criteria, is used during the integration process. At the beginning of each time step, the stress-strain relationship is referred to obtain the soil properties to be used in that time step. The degradation of soil stiffness with number of loading cycles, modeled based upon the generation of pore water pressure, can be accounted for accurately in this method.

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = -[M]\{I\}\ddot{u}_g \qquad (1)$$

where $[M]$ is the mass matrix, $[C]$ is the viscous damping matrix, $[K]$ is the stiffness matrix, $\ddot{u}$ is the vector of relative nodal accelerations, $\dot{u}$ is the vector of relative nodal velocities, u

is the vector of relative nodal displacements, $\ddot{u}_g$ is the acceleration at the base of the soil column, and $[I]$ is an unit vector.

The nonlinear model developed by Phillips and Hashash (2009) with hysteretic damping reduction factor, referred to as MRDF procedure, has been employed in the DEEPSOIL code, for performing nonlinear non-Masing GRA. The stress-strain behavior for loading and unloading/reloading conditions are shown in Eq. 2 and Eq. 3 respectively.

$$\tau = \frac{G_0 \gamma}{1+\beta\left(\gamma/\gamma_r\right)^s} \qquad (2)$$

$$\tau = F(\gamma_m)\left[2\frac{G_0((\gamma-\gamma_{rev})/2)}{1+\beta((\gamma-\gamma_{rev})/2\gamma_r)^s} - \frac{G_0(\gamma-\gamma_{rev})}{1+\beta(\gamma_m-\gamma_r)^s}\right] + \frac{G_0(\gamma-\gamma_{rev})}{1+\beta(\gamma_m-\gamma_r)^s} + \tau_{rev} \qquad (3)$$

where, γ : given shear strain, γ_r : reference shear strain, β : dimensionless factor, s : dimensionless exponent, γ_{rev} : reversal shear strain, τ_{rev} : reversal shear stress, γ_m : maximum shear strain, $F(\gamma_m)$: reduction factor, G_0 : initial shear modulus.

The pore water pressure generation model for sands (Matasovic 1992), for clays (Matasovic and Vucetic 1995), and the pore water pressure dissipation model (Terzaghi 1925) are implemented in DEEPSOIL code.

Liquefaction susceptibility of a site can be identified by computing the factor of safety (FOS) value for various soil layers. FOS can be defined as a ratio of cyclic resistance ratio (CRR), which is indicative of the soil resistance, to the cyclic stress ratio (CSR), which depends upon the stresses generated in soil due to seismic loading. A factor of safety value greater than 1 indicates that a particular layer in a soil profile is safe against liquefaction. CRR can be evaluated either from in situ tests or from laboratory tests (Seed *et al.* 1985) and CSR can be determined from earthquake loading (Seed and Idriss 1971).

2 MODELING OF SOIL PROFILE AND INPUT DETAILS

2 .1 *Regional geology*

Agartala city consists of mainly stretches of plain land along the Haora River, extending to the low lying hills on its northern parts. For the present study, a soil profile from the central part of Agartala is considered. The subsurface profile in this region, is composed of interbedded layers of clayey silts and sandy layers. Water table is quite shallow and it is located within a depth of 2 m from the ground surface in most parts. The shear wave velocity profile for this site has been obtained from measured SPT-N values based on an empirical correlation (Imai and Tonouchi 1982).

2 .2 *Methodology*

The stiffness (modulus reduction curve) and damping ratio for different soil layers have been modeled using the formulations of Ishibashi and Zhang (1993). These formulations incorporate soil properties like confining pressure, overconsolidation ratio, plasticity index, angle of internal friction to name a few. The modulus reduction and the damping curves are then fitted using MRDF procedure, to define the nonlinear stress-strain model parameters. The small-strain viscous damping has been considered to be frequency independent (Phillips and Hashash 2009).

Liquefaction susceptibility of various layers in the soil column is identified using the cyclic stress approach. CSR, the reduction factor, and CRR are evaluated and, thereby, the factor of safety is obtained to assess the liquefaction potential.

2 .3 *Description of soil profile*

The soil profile considered in this study consists of a clayey silt layer sandwiched between layers of fine and medium to dense sands. The total depth of soil profile is 20 m. Ground water table is found at a depth of 1.3 m from the existing ground level. Figure 1 depicts the subsurface strata and the shear wave velocity (V_s) variation with depth of the soil deposit.

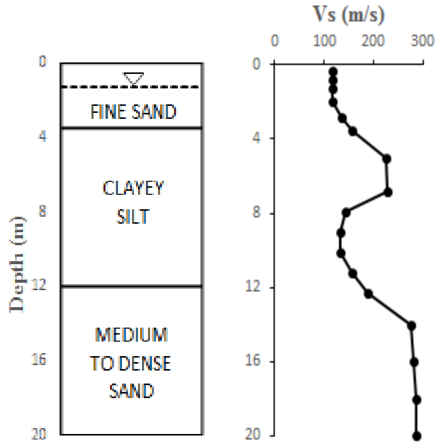

Figure 1. Soil profile of Agartala city and corresponding shear wave velocity profile

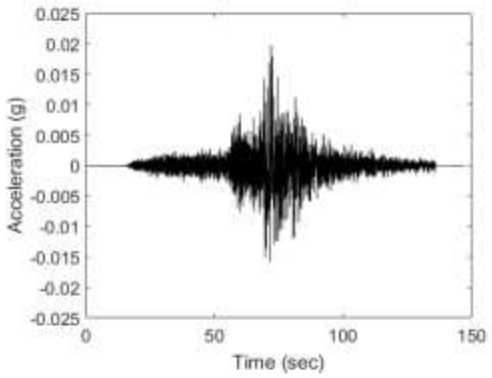

Figure 2. Acceleration time history of the recorded Sikkim earthquake motion (PBRA=0.02g)

2 .4 *Description of seismic loading*

The Sikkim (2011) earthquake strong ground motion recorded near Agartala region, with peak bedrock level acceleration (PBRA) of 0.02g (Figure 2) and the three scaled-up components of the motion with PBRA of 0.04g, 0.08g and 0.18g, have been used as input for the present analysis. According to IS: 1893-I (2002), the zone factor (Z) for Agartala is defined as 0.36g. It indicates the maximum possible ground accelerations based on the perceived maximum seismic risk. The design basis earthquake (DBE) for Agartala can be obtained as 0.18g, i.e. DBE = Z/2 (IS: 1893-I 2002). Thus, the value of 0.18g PBRA has been selected as a limiting value to scale up the components of strong ground motion. These motions have been applied at the base of the soil profile.

3 RESULTS AND DISCUSSIONS

The soil profile is analyzed for the four components of Sikkim earthquake motion having different PBRA. The response of soil subjected to these input motions, is presented in the form of PHA profiles, amplification factor (AF), shear strain and response spectra. Subsequently, liquefaction susceptibility of the soil deposit is also determined.

3 .1 *Peak horizontal acceleration and amplification factor*

Figure 3 shows the PHA profiles obtained for the four input motion components. The peak ground acceleration (PGA), i.e. PHA at ground surface, is observed to be greater than the PBRA of input motion for each of the analyses. For the 0.18g PBRA motion, the PHA variation with depth is observed to be abrupt. Amplification of ground motion is observed from the bottom of the profile up to about 10 m depth in the bottom sand layer, followed by de-amplification in the clayey silt layer. Further on, amplification of motion is seen in the top sand layer.

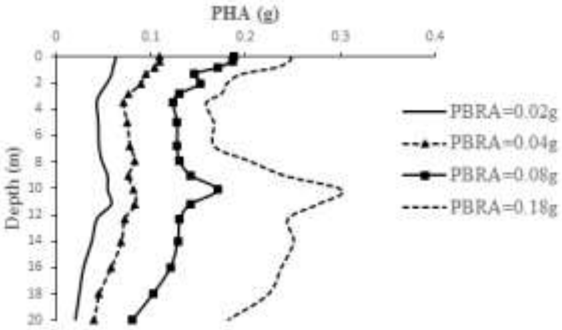

Figure 3. PHA variation with depth in soil profile

Table 1. PGA obtained for motions with different PBRAs (AF shown in brackets)

PBRA	PGA (AF)
0.02g	0.06g (3)
0.04g	0.11g (2.75)
0.08g	0.19g (2)
0.18g	0.25g (1.39)

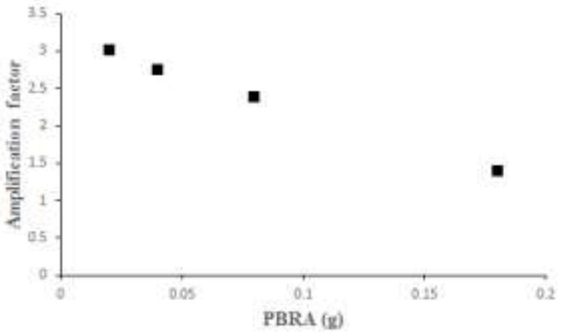

Figure 4. AF variation with PBRA of input motion

The observed PGA and amplification factor (ratio of PGA to PBRA) for the four input motions is presented in Table 1. It can be seen that AF decreases with an increase in PBRA of input motion (Figure 4). This trend has also been reported in other literature (Warnitchai and Lisantono 1996, Aashford *et al.* 2 000).

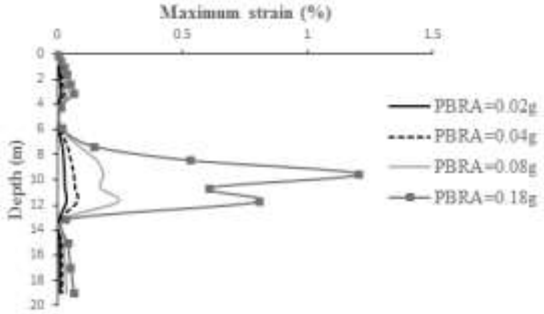

Figure 5. Maximum shear strain variation along with depth in soil profile

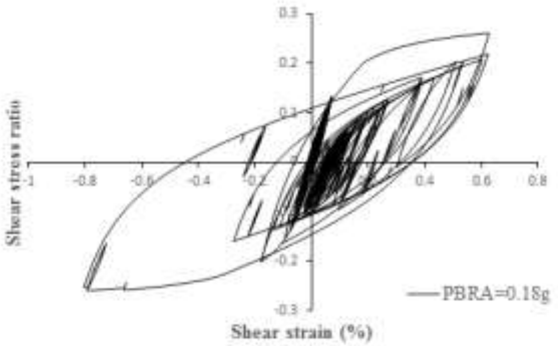

Figure 6. Stress-strain loop observed for clayey silt layer (shear stress ratio indicates the ratio of shear stress observed to the corresponding effective vertical stress at the same depth)

3 .2 *Shear strain and hysteretic loop*

The maximum shear strain observed at various depths in the soil profile for the four input motions is shown in Figure 5. It can be seen that the maximum strains produced on account of motions with 0.02g, 0.04g and 0.08g PBRA is low (less than 0.2%). However, significant maximum shear strains (about 1% and greater) are observed in soil layers at around a depth of 8 - 12 m for the 0.18g PBRA input motion. No residual strains are observed in any soil layer for the 0.02g, 0.04g and 0.08g PBRA motion components. However, some amount of residual strain is observed in the middle clayey silt layer for the 0.18g PBRA motion, as depicted in the stress-strain hysteretic loop shown in Figure 6.

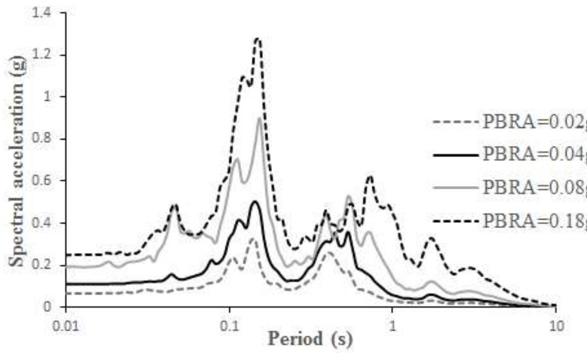

Figure 7. Response spectra plots for four input motions

3 .3 *Response spectra*

The variation of spectral acceleration with the natural period of any system is depicted by a response spectra plot. A response spectrum indicates the maximum response of a single-degree-of-freedom system, subjected to a particular input load, as a function of the natural period and damping ratio of the system.

It serves as an essential guideline for seismic design of structures. The response spectra obtained for the four motion components are shown in Figure 7. It can be seen that highest responses are expected for structures having low natural period in the range of 0.1 - 0.2 s.

3 .4 *Liquefaction potential*

The FOS against liquefaction at various depths is computed for the four motions as shown in Figure 8. It is observed that no liquefaction is expected for the recorded motion with 0.02g PBRA. However, for the other three motions liquefaction is seen to occur up to a depth of almost 12 m. The depth and the extent of the zone of liquefaction is found to increase with the increase in peak acceleration of input motion.

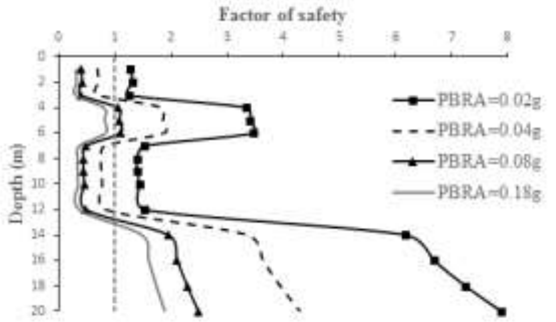

Figure 8. Factor of safety variation with depth in soil profile

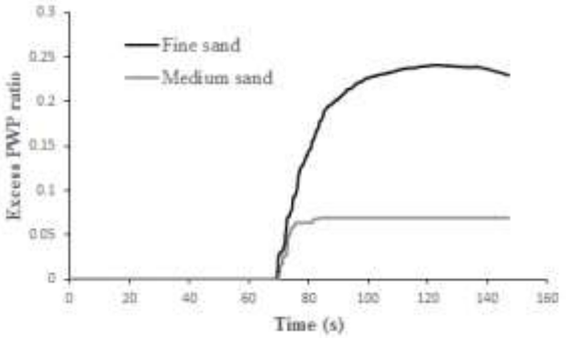

Figure 9. Excess PWP ratio variation with time in the overlying fine and underlying medium sand layers for 0.18g PBRA seismic motion

3 .5 *Excess pore-water pressure ratio*

Figure 9 shows the excess pore-water pressure (PWP) ratio variation with time obtained for the top fine sand layer. Excess PWP ratio is defined as the ratio of the excess PWP built up at a particular depth in a soil layer to the effective vertical overburden pressure at the same depth. It is seen that the PWP rise becomes considerable almost 70 s after the commencement of seismic loading. Negligible excess PWP build up is seen in the bottom medium sand layer owing to its high shear wave velocity (higher initial stiffness, thus lesser stiffness degradation). It can be observed from the Figures 8 and 9 that the interpretations are contradicting each other. The estimated FoS suggests that liquefaction is expected within depths of 0-4 m and 8-12 m, while the excess pore-water pressure ratio does not rise to significant values for both the medium and fine sand layers, thus exhibiting no significant reduction in effective stress. There has been a long debate amongst the researchers in this field as whether the FoS is a proper way to exhibit liquefaction susceptibility. The obtained results further reinforce the ambiguity. More in-depth understanding and studies are required to comprehend the observation.

4 CONCLUSIONS

In this paper, a one dimenensional nonlinear GRA has been conducted for a typical soil profile located in central part Agartala city. Seismic motions having four different values of PBRA have been used as input motions. Ground motion has been seen to amplify at this site for all components of input motion. Amplification factor has been seen to decrease with the increase in PBRA value of motion. The maximum strains produced in the soil layers for input motions with 0.02g, 0.04g, and 0.08g PBRA, are less than 0.2%. A maximum strain of about 1% has been observed in the clayey silt layer of the soil profile for the 0.18g PBRA motion. Thus, it indicates the probability of higher and residual strains developing in these soils for input motions having high PBRA value around 0.18g. The response spectra obtained for this soil profile have shown high responses for structures having natural period in the range 0.1 - 0.2 sec. Thus, it can be stated that the probability of seismic risk associated with structures having lower natural periods is significantly high.

Further on, he liquefaction potential of the proposed site has been identified using cyclic stress approach. Liquefaction potential has been evaluated on the basis of computed factor of safety values at various depths. For input motions having PBRA values greater than 0.02g, the soil deposit has been seen to be highly susceptible to liquefaction. The top 12 m depth of the soil column has been identified as potentially liquefiable. However, the same is not reflected by the developed pore-water pressures, and needs further investigation.

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