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1D Effective Stress Site Response Analysis; Using Stress Based Pore Pressure Model and Plasticity Model

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***Abstract*--The accumulated stress based porewater pressure (PWP) generation model is a simplified model using the concept of damage parameter. The only input of this PWP model is liquefaction resistance curve (CRR-N). The model is very useful since the CSR-N curves can be developed empirically from in-situ penetration tests measurements. In this research work the estimation of excess PWP development during seismic loading by using stress based PWP generation model is compared with a rigorous plasticity model. One dimensional (1D) effective stress nonlinear site response analyses were conducted in DEEPSOIL and Opensees using the stress based PWP model and PressureDependentMultiYield02 (PDMY2) model, respectively. The site response analysis were performed on a sand column 30 m in depth comprises of a low density liquefiable layer in between two dense non-liquefiable layers. Three bed rock outcropping motions with peak ground acceleration (PGA) level of 0.11 g, 0.124 g and 0.357 g were used as input motion in the analysis. The maximum r_u profiles computed from the two models were compared and analyzed. The r_u time histories at the center of the non-liquefiable layers and liquefiable layer were also compared. The comparisons revealed that the two models used in this study compute most comparable r_u values. The computed r_u is also found in line with density of soil and the PGA of the input ground motions where the r_u increases with increase in the PGA and decreases with increasing density.**

***Keywords*-Liquefaction, Porewater Pressure Model, Excess Pore Pressure Ratio, Site Response, Effective Stress**

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I. INTRODUCTION

THE ground motions and surface response are significantly modified Excess porewater pressure (PWP) generation during earthquake shaking [1, 2], suggesting that effective stress nonlinear site response analysis should be performed for seismic design. The nonlinear site response analysis are performed with PWP coupling. Effective stress nonlinear site response analysis are also performed to estimate the excess PWP development and liquefaction potential of soil strata subjected to strong ground motions. One dimensional (1D) nonlinear site response analysis is widely accepted. The PWP models are incorporated in site response analysis programs to predict the buildup of excess porewater pressure during dynamic loading. Various researchers have developed models to capture the buildup of excess PWP during seismic or cyclic loading. Most advance models including plasticity constitutive soil models have been incorporated in finite element computer programs. However, the input parameters selecting for such models make their use practically impossible or very limited. Simpler PWP models have also been developed which predict the buildup of excess PWP based on the accumulated shear strain, but the rarely performed undrained strain controlled cyclic tests data are always needed to select the input for these models. Which is one of the reasons in selecting input parameters inconvenient for the strain based PWP models and is responsible for the rarely use of effective stress dynamic analysis in practice. Undrained stress controlled tests on the other hand are widely performed in the lab to predict the liquefaction potential and cyclic shear strength of soil. Park, et al. [3] presented the accumulated stress based PWP generation model given in (1). The model is the modified form of the Seed and Idriss [4] PWP prediction model by introducing the concept of damage parameter. The model is very useful since all the input parameters of the model can be selected from liquefaction resistance curve (CRR – N), where CRR is the cyclic resistance ratio and N is the number of cycles. In case the site-specific liquefaction resistance curves are not available, they can be developed empirically by incorporating the normalized liquefaction resistance curves with the in-situ empirical liquefaction resistance correlations knowing site specific in-situ measurements i.e (SPT, CPT, Vs) [5]. This make the model particularly appropriate since site-specific in-situ parameters (*SPT*, *CPT* or V_s) are always available.

$$r_u = \frac{2}{\pi}\arcsin\left(\frac{D}{D_{ru=1.0}}\right)^{\frac{1}{2\beta}} \qquad (1)$$

where β is curve fitting parameter, D is the damage parameter and $D_{ru=1.0}$ is the damage parameter at $r_u=1$. Park, et al. [3] has discussed and presented in detail the selection of the model parameters from CRR – N curves.

The accumulated stress based pore water pressure model has been compared and verified with the laboratory test results [3], however, it has yet not been used in the site response analysis. In this paper, the accumulated stress based pore pressure model is used in 1D effective stress site response analysis. The results of the model are also compared with the PDMY2 (PressureDependentMultiYield02). One dimensional nonlinear effective stress site response analysis was performed in DEEPSOIL using the stress based PWP generation model and in OpenSees using PDMY2 (PressureDependentMultiYield02) model. DEEPSOIL is a one-dimensional site response analysis computer program that can perform nonlinear analyses in time domain with and without generation of excess PWP [6]. OpenSees (Open System for Earthquake Engineering Simulation) is an open source finite element software which provide a platform for modeling the dynamic response of geotechnical structural systems [7].

II. EFFECTIVE STRESS NONLINEAR SITE RESPONSE ANALYSIS

1D effective stress nonlinear site response analyses was made on an Ottawa sand column of 30 m depth. The sand column comprises of a liquefiable layer with relative density (D_r) 40% in between two dense layers with D_r 80%, as shown in Fig. 1 a. The shear wave velocity (V_s) of the profile was calculated from the empirical correlation proposed by Hardin and Richart Jr [8] as follows;

$$V_s = (91 - 44.6\times e)(\sigma_{\text{mean}})^{0.25} \qquad (2)$$

where e is voids ratio and σ_{mean} is mean confining pressure. Average shear wave velocity of each layer was used in modeling the sand column, as given in Fig. 1 b.

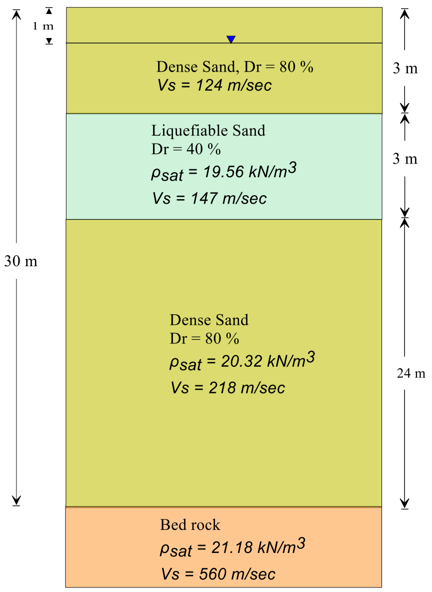

Fig. 1. (a) Soil profiles (b) Shear wave velocity profile

Three input ground motions were used in the site response analysis having PGA 0.357g, 0.124g and 0.11g (LomaGilroy motion was scaled), as presented in Fig. 2. The details of the input motions are given in Table I. The modeling of the sand profile and model parameters for DEEPSOIL and OpenSees are given in detail in the following section.

TABLE I:

Summary of the Input Ground Motions

Motion Name	Record Number	Magnitude	R_{rup} (*km*)	*PGA* (*g*)
LomaGilroy	P0764	6.9	11.6	0.357
Coyote	P0154	5.7	26.5	0.124

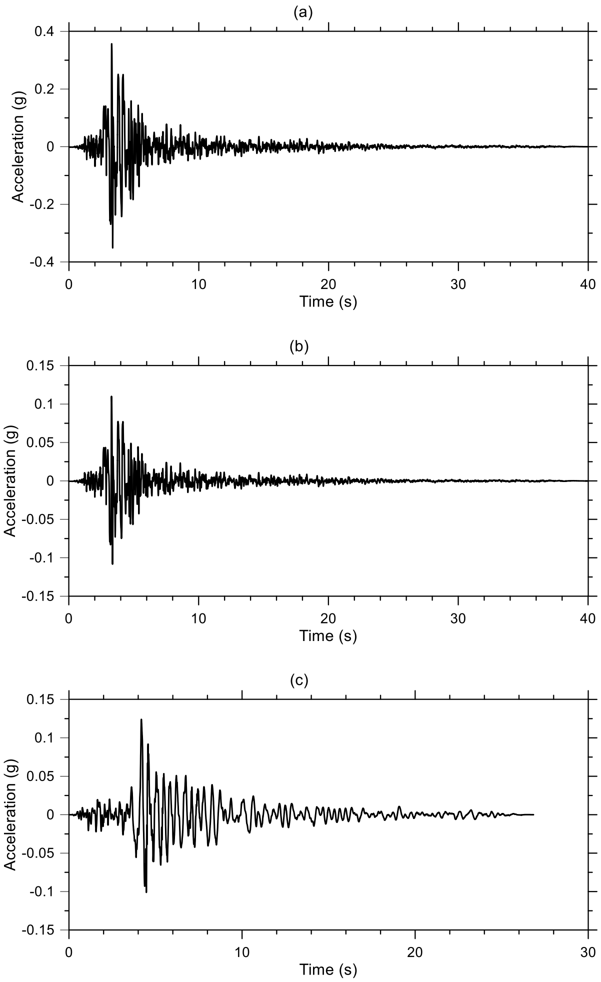

Fig. 2. Input ground motions (a) Loma Gilroy (PGA = 0.357g) (b) Loma Gilroy (PGA = 0.11g) Coyote (PGA = 0.124g)

A. Deepsoil

The nonlinear soil behavior in DEEPSOIL was modeled using modified pressure dependent hyperbolic constitutive model of [9] known as Modified Kondner Zelasko (MKZ) model in DEEPSOIL. Shear strength of the soil was defined by using Darendeli (2001) modulus reduction and damping curves for each layer in the soil column. The dynamic curves fitting tool (MRDF) with Darendeli reduction factor was used to capture the non-masing re/unloading hysteresis behavior. The derived normalized shear modulus reduction and damping curves are shown in Fig. 3. The layers thickness in DEEPSOIL was adjusted such that the frequency of each layer was greater than 30 Hz which is the recommended maximum frequency. The maximum frequency is the highest frequency that can be propagated through the soil profile and is calculated as: $f_{max} = V_S/4H$, where V_S is the shear wave velocity of the layer, and H is the layer thickness. The bottom of the profile was model as elastic half space with bed rock shear wave velocity of 760 m/sec. Stress based PWP generation model was used to assess the development of excess pore water pressure.

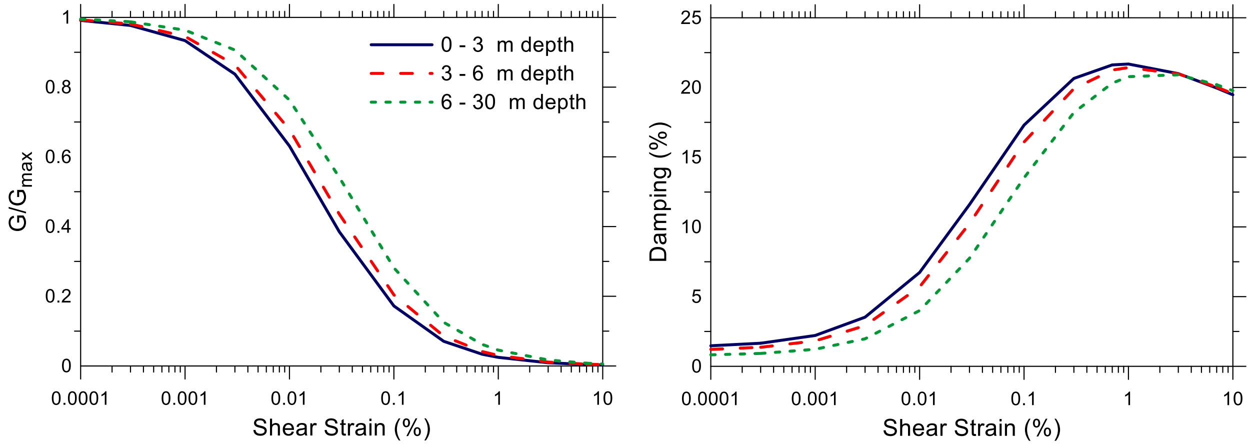

Fig. 3. Modulus reduction and damping curve

The stress based PWP model parameter for Ottawa sand were calculated by fitting the liquefaction resistance curves given in Fig. 4 [5], as describe by Park, et al. [3]. The calculated model parameters are presented in Table II.

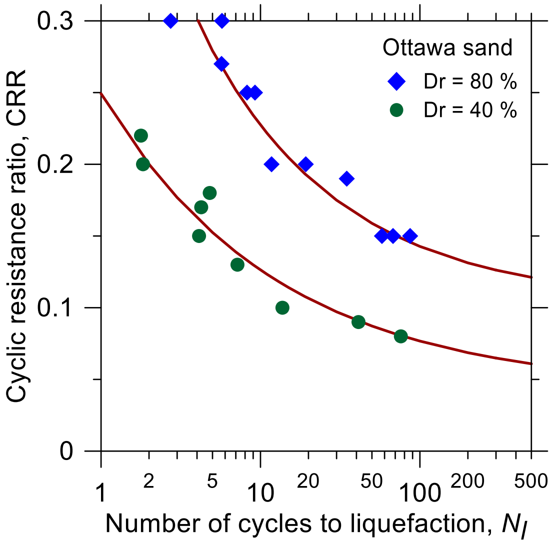

Fig. 4. Liquefaction resistance curve fitted with Park et al. (2014) Model

TABLE II

Stress Based Pore Pressure Model Parameters for Ottawa Sands

Model parameters	Dr = 40%	Dr = 80%
CSR_t	0.043	0.104
α	2.54	1.98
β	1.2	1.3
$D_{ru} = 1$	0.072	0.63

B. *OpenSees*

We also perform one dimensional site response analysis of the sand column shown in Fig. 1, using OpenSees. The PressureDependentMultiYield02 (PDMY2) material was used with 9_4_QuadUP element to model the sand column. The PDMY2 model is plasticity material based on the multi-surface plasticity approach of Prevost [10]. The PDMY2 material uses a non-associative flow rule and Drucker-Prager type of yield surfaces [11-14]. 9_4_QuadUP element is a 9-node quadrilateral plane-strain solid-fluid fully coupled element, having three degree-of-freedom (DOF) on each of the four corner nodes: representing the solid displacement in horizontal and vertical direction and pore water pressure respectively. The other five interior nodes have two DOF for solid displacement in horizontal and vertical direction respectively. This element enables the model to simulate the changes in effective stresses and pore pressure when dynamic loading is applied.

The sand column was modeled with a single column of 9-node quadrilateral plane-strain element, as shown in Fig. 5. The nodes at the base of soil column were fixed against vertical displacement and those above the groundwater table were fixed in the pore pressure DOF to provide undrained condition below the water level and drained condition above the water level respectively. Nodes at the same location were constrained to the same displacement to simulate 1D analysis and the simple shear condition. This was done by using the Opensees equal DOF command. Viscous dashpot boundary [15] were used to model half-space, as suggested by Stewart, et al. [16].

The PDMY2 model parameters for Ottawa sand derived from the element level analysis performed by Mandokhail, et al. [17], given in Table III were used in this study. The r_u values were calculated from the difference of the initial effective stress (σ'_{v0}) and the minimum effective stress ($\sigma'_{v,min}$) normalized by σ'_{v0}, measured during the analysis: $r_u = (\sigma'_{v0} - \sigma'_{v,min})/\sigma'_{v0}$.

TABLE III

Calibrated Parameters of PDMY2 Model (Opensees) for Ottawa Sand (Mandokhail et al., 2017)

Parameters	*Dr* = 40%	*Suggested *Dr* = 40%	*Dr* = 80%	*Suggested *Dr* = 80%
Friction angle ϕ (deg.)	32	32	36	36.5
Shear strain at failure, γ_f	0.1	0.1	0.1	0.1
Reference pressure (*kPa*)	101	101	101	101
Pressure dependent coefficient	0.5	0.5	0.5	0.5
Phase transformation angle, ϕ_{PT} (deg.)	28	26	20	26
Contraction parameter 1, ct_1	0.067	0.067	0.01	0.013
Contraction parameter 2, ct_2	5.0	-	5.0	-
Contraction parameter 3, ct_3	0.2	0.23	0.0	0.0
Dilation parameter 1, dil_1	0.02	0.06	0.32	0.3
Dilation parameter 2, dil_2	2.5	-	2.5	-
Dilation parameter 3, dil_3	0.2	0.27	0.0	0.0
Initial void ratio, *e*	0.66	-	0.55	-

* Parameters range suggested by Mazzoni et al., [18]

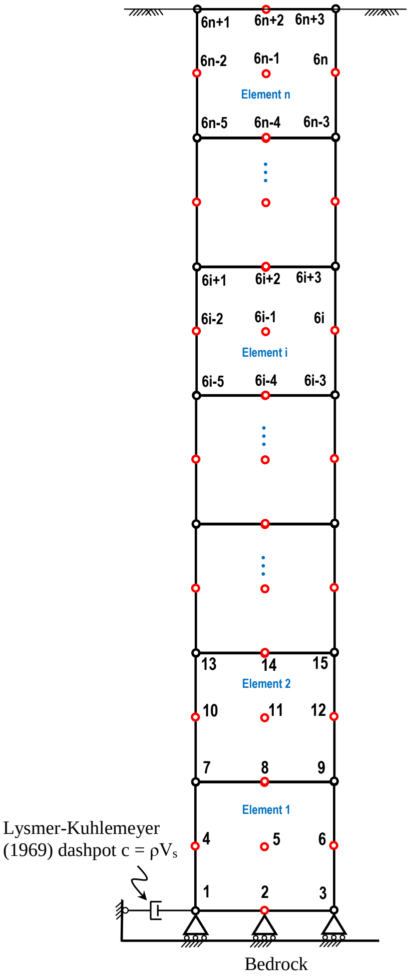

Fig. 5. Schematic representation of the site response model. Node numbers in blue, element numbers in red.

III. RESULTS AND DISCUSSION

The site response analysis results of DEEPSOIL and OpenSees are given and compared in Fig. 6 and Fig. 7. The developed excess PWP in terms of excess pore pressure ratio (r_u) time histories at mid depth of liquefiable layer and dense layer computed from DEEPSOIL and OpenSees are compared in Fig. 6. To closely analyze the buildup of r_u the results are ploted up to 10 sec, as shown on the right in Fig. 6. From the comparisons it can be seen that the two models use in DEEPSOIL and OpenSees predict the development of excess pore pressure very similar to each other. Due to the space shortage the time histories of r_u from input motion of PGA 0.1g and 0.124g for dense layer are not shown in the paper.

The maximum excess pore pressure ratio profile of the sand column are presented in Fig. 7. The r_u profile was made by extracting the maximum r_u computed at different depths in the profile. The comparison shows that the r_u profiles from DEEPSOIL are in good agreement with those of OpenSees at all depths in all the cases. The generated excess pore pressure values are higher in low density liquefiable layer and smaller in dense non-liquefiable layers in all the cases. r_u is also in line with the bed rock input motion PGA where it increases with increase in the PGA level.

IV. CONCLUSION

One dimensional effective stress nonlinear site response analysis are always performed to estimate the ground surface response, development of excess PWP and liquefaction potential of saturated soil strata subjected to strong earthquakes. Various models have been proposed to predict the buildup of PWP during the earthquakes. However, the input parameters selection of such models is always difficult. Accumulated stress based pore pressure model is the simplest model for which all the input parameters can be defined from the from liquefaction resistance curve (CRR – N). Though, the stress based pore pressure model is the simplest, but yet not used in the 1D site response analysis.

In this study, 1D effective stress nonlinear site response analysis were performed in DEEPSOIL and OpenSees by using the stress based PWP generation model and PDMY2 model, respectively. The intension of the study was to compare the results of the stress based PWP generation model with the vigorous plasticity model, PressureDependentMultiYield02 (PDMY2) model. The study shows that the predicted r_u by stress based PWP model is in good match with PDMY2 model. The two models have shown very similar results by comparing the r_u time histories. The $r_{u,(max)}$ (maximum PWP) profiles along the depth of sand column computed with the stress based pore pressure model are also in good match with PDMY2 model. The predicted r_u values are also in line with the PGA level of the input ground motion and density of the soil, where it increases with increasing PGA level of input motion and decreases with increasing density of soil layers. The outcome of the study suggested that the accumulated stress based pore pressure model can be used confidently in the effective stress site response analysis.

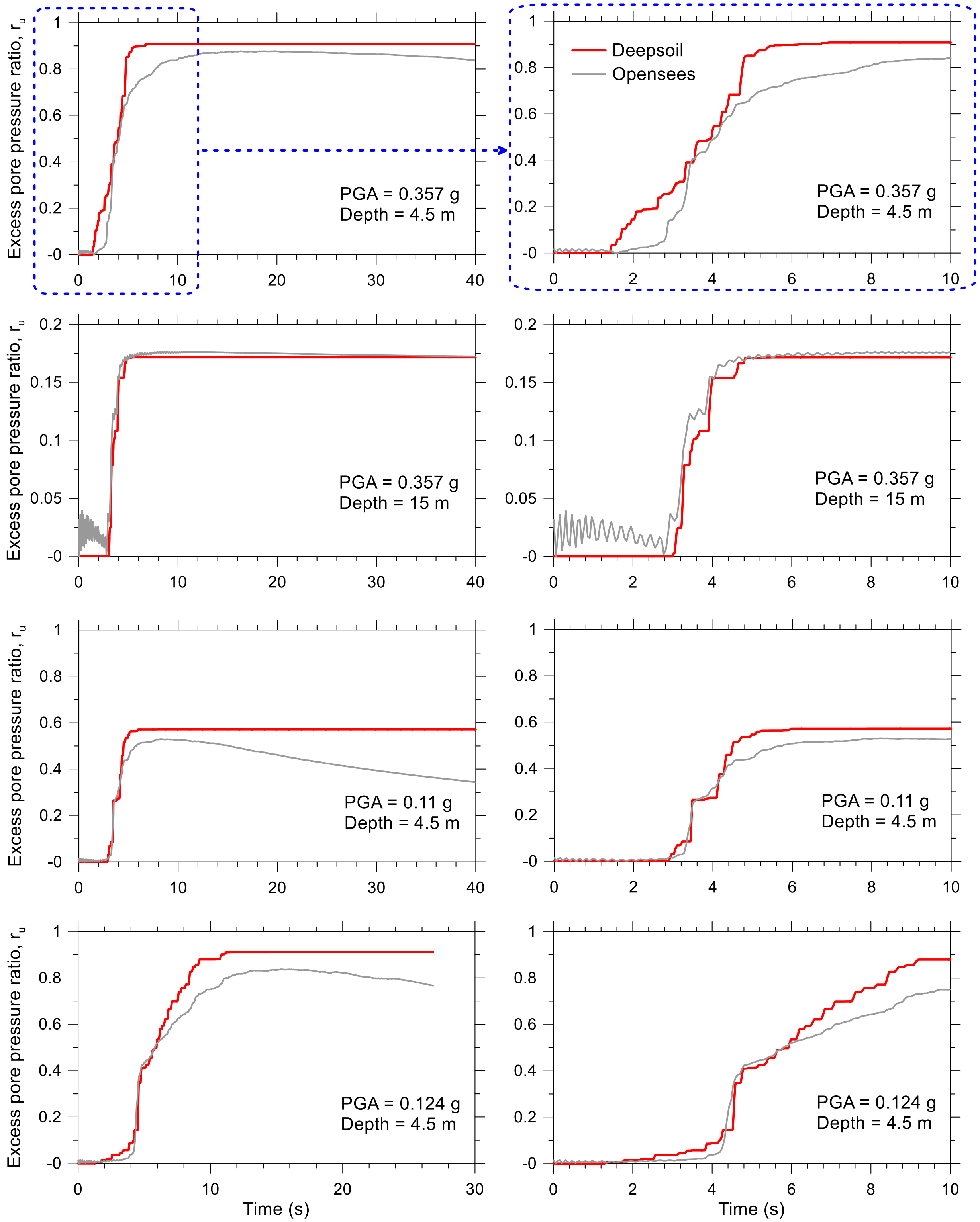

Fig. 6. Comparison of r_u at different depth in the profile by using stress based PWP model (Deepsoil) and PDMY2 model (Opensees)

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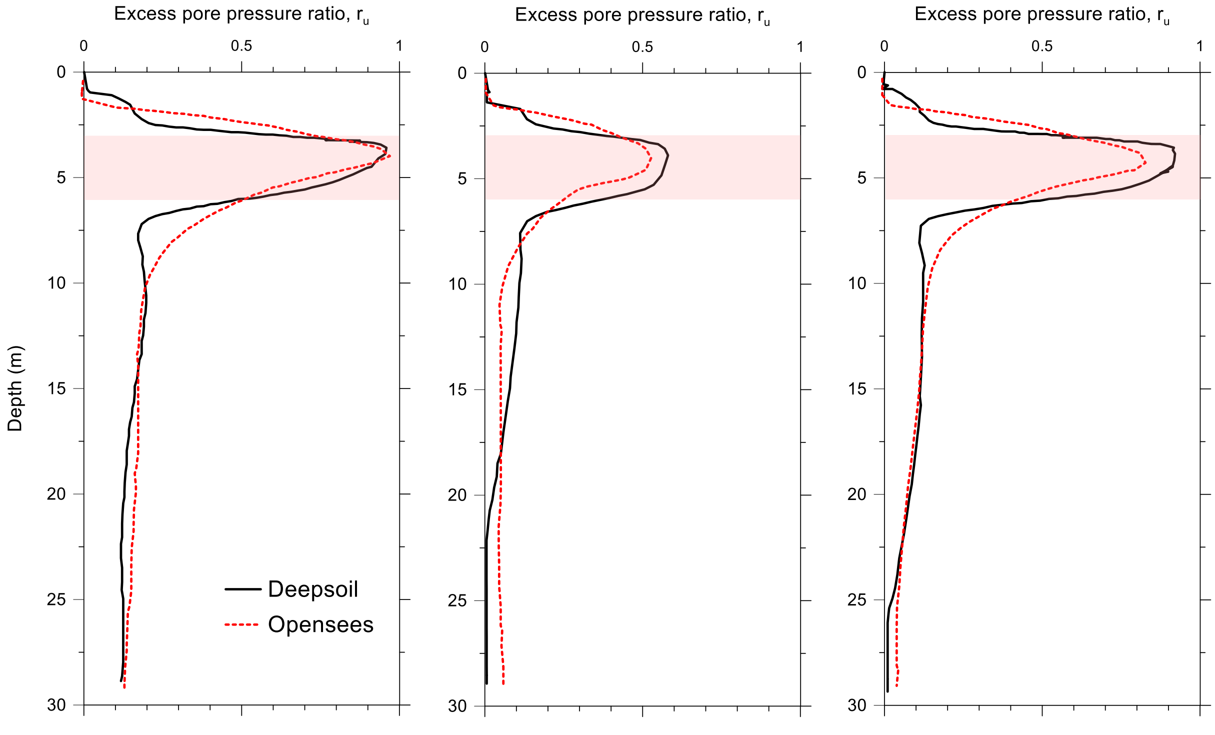

(a) (b) (c)

Fig. 7. Comparison of maximum r_u profile calculated by using stress based PWP model (Deepsoil) and PDMY2 model (Opensees) (a) 0.357 *g* (b) 0.11 *g* (c) 0.124*g*

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