SEISMIC PORE WATER PRESSURE GENERATION MODELS: NUMERICAL EVALUATION AND COMPARISON

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ABSTRACT:

Researchers have attempted to model excess pore water pressure via numerical modeling, in order to estimate the potential of liquefaction. The attempt of this work is numerical evaluation of excess pore water pressure models using a fully coupled effective stress and uncoupled total stress analysis. For this aim, several cyclic and monotonic element tests and a level ground centrifuge test of VELACS project [1] were utilized. Equivalent linear and non linear numerical models were used to evaluate the excess pore water pressure. Comparing the excess pore pressure buildup time histories of the numerical and experimental models showed that the equivalent linear method can predict better the excess pore water pressure than the non linear approach, but it can not concern the presence of pore pressure in the calculation of the shear strain.

KEYWORDS: Excess pore water pressure, effective stress, total stress, equivalent linear, non linear

1. INTRODUCTION

Estimation of liquefaction is one of the main objectives in geotechnical engineering. For this purpose, several numerical and experimental methods have been proposed. An important stage to predict the liquefaction is the prediction of excess pore water pressure at a given point. This is due to the fact that when a cyclic loading is imposed to a sandy saturated soil, the excess pore water pressure will be increased until the value of excess pore water pressure reaches to the initial confining pressure, and this will lead to happening of liquefaction.

There are two main approaches for studying the stability of soil deposits subjected to earthquake loading, the total stress and the effective stress method. Equivalent linear and non linear methods are the numerical models that have been proposed to predict the undrained cyclic behavior of soil and consequently the generation of the pore water pressure.

The generation of excess pore water pressure can be simulated using the equivalent linear model, which is extensively described in the geotechnical earthquake engineering literature [2-5]. Examples of data for equivalent linear model can be found in Hardin and Drnevitch [6], Kramer [4] Seed and Idriss [3], Seed et al. [2], Sun et al. [7], and Vucetic and Dobry [8]. In this method the calculation is on the base of observing the rate of pore pressure development in cyclic loading tests. One reason for using the equivalent linear model more often is that it needs few parameters. This technique is based on the idea of replacing a non-linear system by a related linear system in such a way that the difference between the two is minimized in some statistical sense [9-12]. This approach provides results that are well compared with field measurements and are widely used in engineering practice.

Because soils exhibit a wide range of complex responses when subjected to arbitrary loading, the best method is nonlinear stress-strain response analysis. Excess pore water pressure produced during liquefaction can be calculated from the correlation between pore pressure response and the corresponding volume change tendency of dry soils obtained from nonlinear analysis (e.g. Martin et al. [13]). The Mohr-Coulomb constitutive model with a non-associate flow rule coupled with the Martin et al. [13] excess pore water pressure build up model have been implemented in the software to obtain cyclic response of saturated soils.

The VELACS model # 1 centrifuge test [1] representing a level ground site constituted of Nevada sand at 40% relative density has been numerically simulated with both equivalent linear and non linear methods in the current study. The main goal of this study is to evaluate the capability of these approaches in the prediction of excess pore water pressure variations during cyclic loading. The preliminary analyses and the comparisons between measured and numerical results showed that their accuracies are not satisfactory for all conditions. The results of the cyclic and monotonic element tests were utilized in order to set up the calibration parameters of the centrifuge model #1 test for the Nevada 40% sand. Two widely used numerical softwares with the basis of equivalent linear (GEO-SLOPE) and the non-linear (FLAC 2D) approaches, were used.

2. THEORITICAL BACKGROUND

The non-linear numerical modeling provided by the effective stress method is implemented by means of FLAC, a finite difference based software, for simulating liquefaction. The software used the modified Mohr-Coulomb failure criterion, Finn model that incorporates two equations correlating the volumetric strain induced by the cyclic shear strain and excess pore water pressure produced during cyclic loading. As mentioned above, the pore water pressure generation can be computed from two sets of equation: the Martin et al. [13] and the Byrne [14] formulations in which the volumetric strain that was produced in any cycle of loading is dependent on the shear strain that was formed during that cycle as well as the previously accumulated volumetric strain. Martin et al. proposed the following equation to compute the volumetric strain increment:

$$\Delta\varepsilon_v = C_1 \cdot (\gamma - C_2\varepsilon_v) + \frac{C_3{\varepsilon_v}^2}{(\gamma + C_4\varepsilon_v)} \tag{2.1}$$

Where $\Delta\varepsilon_v$ is the cumulative volumetric strain increment over the current cycle, ε_v the volumetric strain over the previous cycles, γ the amplitude of the shear strain for the current cycle and C_1 to C_4 : are constants dependent on the volumetric strain behavior of the sand.

Byrne (1991) proposed a modified and simpler volume change model with two calibration parameters. The governing equation was expressed as:

$$\frac{\Delta\varepsilon_{vd}}{\gamma} = C_1 \cdot \exp \cdot (-C_2 \cdot \frac{\varepsilon_{vd}}{\gamma}) \tag{2.2}$$

Where C_1 and C_2 are model constants.

In the equivalent linear method, the numerical model developed in the total stress approach, and the level of excess pore water pressure development can be predicted in based on the cyclic stress approach in which it is directly related to the amplitude of cyclic stress and the number of the stress cycles. It has been found that the rate of pore pressure build up generally lies in a fairly narrow range when plotted in the normalized form and for the simple shear test the band is shown in Figure 1. Seed et al. [15] found that the pore pressure ratio function can be obtained by the following equation:

$$r_u = \frac{1}{2} + \frac{1}{\pi}\arcsin[2({N}/{N_L})^{1/\alpha} - 1)] \tag{2.3}$$

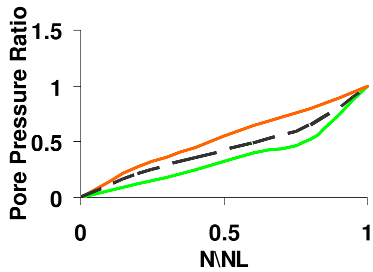

Figure1 Rate of Pore-Water Pressure Buildup in Cyclic Simple Shear Tests

Where α is a constant that specifies the shape of the curve, N is the stress cycle and N_L is the stress cycle required for producing liquefaction and decreases with increasing the cyclic stress amplitude. According to this equation the cyclic ratio must be determined to calculate the pore pressure ratio. This equation has been properly implemented in the equivalent linear method by GEOSLOPE software and is used herein.

The objective of this study is to evaluate the capability of the above mentioned numerical methods in the prediction of excess pore water pressure in Nevada 40% Sand. For this purpose the experimental test conducted in the VELACS project [1] was modeled and the results of excess pore water pressure obtained from the numerical modeling are compared with the test data. Details of the former modeling, i.e. effective stress numerical method performed by FLAC [15], were completely described in Nabili et al. [16]. The procedure utilized to perform total stress analysis by GEOSLOPE is cited in the subsequent section.

3-TOTAL STRESS NUMERICAL MODELING

To model the centrifuge test by this method, it is necessary to calculate the required parameters including shear modulus and damping ratio curves. Other input such as $r_u - N/N_L$ and $CSR - N/N_L$ relations are required to set the program for calculation of EPWP during excitation. As described in the following sections, all of the mentioned parameters and diagrams have been obtained from various test results conducted on Nevada 40% Sand.

3.1. Calculating the Parameters of the Hysteretic Shear Stress-Shear Strain Curve

The parameters that represent the behavior of the soil in equivalent linear framework are the shear modulus reduction, $G/G_{\max}$, and the representative energy loss damping ratio, ξ.

Numerous shear modulus reduction curves have been proposed in the literature, Ishibashi and Zhang [17] proposed one of the most important G-reduction relation since their curves are functions of both effective confining stress (σ'_m) and plasticity index (I_p):

$$G/G_{\max} = K(\gamma, PI) \cdot (\sigma'_m)^{m(\gamma,PI)-m_0} \tag{3.1}$$

Where

$$K(\gamma, PI) = 0.5\left\{1 + \tanh\left[\frac{0.000102 \quad + n(PI)^{0.492}}{\gamma}\right]\right\} \tag{3.2}$$

$$m(\gamma, PI) - m_0 = 0.272\left\{1 - \tanh\left[\ln\left(\frac{0.000556}{\gamma}\right)^{0.40}\right]\right\}\exp\left(-0.0145 \ PI^{13}\right) \tag{3.3}$$

To calculate the shear modulus reduction, cyclic simple shear test conducted in VELACS project have been utilized, since the simple shear test can best simulate earthquake excitation in a level site. Results of a test with relative density equal to 40% and confining pressure equal to 80kPa have been used. The first step for acquire the shear modulus reduction during cyclic loading is the calculation of the tangent of each of the individual loops. Increment in the cyclic shear strain will result decrease of the shear modulus. The diagram of this reduction versus the cyclic shear strain was sketched, and the curve obtained from the direct simple shear test was compared with the rate calculated from the Ishibashi and Zhang equation. The results are demonstrated in Figure 2 for comparison.

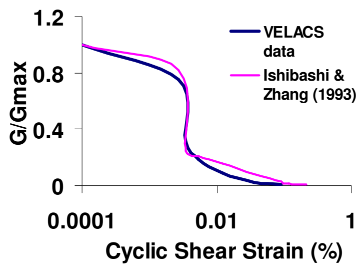

Figure2 Comparison between the result of the Ishibashi and Zhang equation and the test data for shear modulus reduction

As shown, the comparison shows a good agreement which verifies both Ishibashi and Zhang equation and its suitability for Nevada 40% Sand.

For saturated sample subjected to undrained cyclic loading, the shear modulus for each subsequent loop is less than the previous loop, and the damping ratio is greater from the previous one. This is in spite of the fact that the area bounded by hysteresis loop increase as the loading progress. The damping ratio is often given as following equation:

$$\xi = \frac{1}{4\pi} \cdot \frac{\Delta W_1}{W} \tag{3.4}$$

Where ξ : the damping ratio, ΔW_1 **:** Dissipated energy per unit volume in one hysteresis loop, W: Energy stored in an elastic material having the same shear modulus as the visco-elastic material. Various equations are proposed for predicting the increment of damping ratio through cyclic strain. Ishibashi and Zhang [17] proposed the following equation for damping ratio:

$$\xi = 0.333 \frac{1+\exp(-0.0145 PI^{13})}{2} \left[0.586 \left(\frac{G}{G_{\max}} \right)^2 - 1.547 \frac{G}{G_{\max}} + 1 \right] \tag{3.5}$$

As it shows, damping ratio is a function of plastic index and the shear modulus reduction. Since the Nevada Sand is a granular soil and its plasticity is zero, the parameter that influences the damping ratio is the shear modulus degradation. Figure 3 shows the results of comparison between damping ratio calculated from the Ishibashi and Zhang equation and the value obtained from the data of the undrained cyclic simple shear test. To calculate the damping ratio from the equation (3.4), the dissipated energy per unit volume of material in one cycle of loading (ΔW_1) was calculated and then the maximum energy stored in an elastic material having the same shear modulus as the visco-elastic material (*W*) was computed.

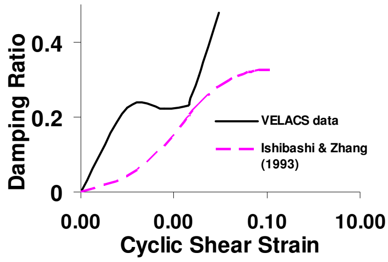

Figure 3 Comparison between the result of the Ishibashi and Zhang equation and the test data for damping ratio

The result of damping ratio computed from the VELACS project and the data calculated from the Ishibashi & Zhang formula do not match overly. It is required to note that the procedure used by Ishibashi & Zhang to propose their relationship is rather different from the one used in the current paper. Their equations were derived by the results of multistage cyclic tests and G or ξ values were recorded at identified cyclic number in each stage. The observed difference between the results may be due to this fact.

3.2. Pore Pressure Ratio versus Cyclic Number Ratio $r_u - N/N_L$

The relation of $r_u - N/N_L$ is required when GEO-SLOPE software is set for seismic PWP estimation. N is number of uniform cycle and N_L is the number of cycles that cause liquefaction. For calculating N_L from the cyclic simple shear test the lower value obtained from following procedure is taken in to account. Firstly from the pore pressure diagram, the time in which the pore pressure reach to the initial confining pressure is obtained and by knowing the frequency of loading, the corresponding number of cycles is obtained. Secondly in the diagram of the shear strain, the number of cycle in which the double amplitude of the shear strain exceeds 5% it will be the time that liquefaction has happened. A series of undrained cyclic simple shear test in the VELACS project and under condition of various confining pressure 80kPa and 160kPa have been considered. The results of comparison obtained from the tests and diagrams proposed by Seed et al. [14] for two tests in the relative density of 54% and 90% have been shown in the Figure 4.

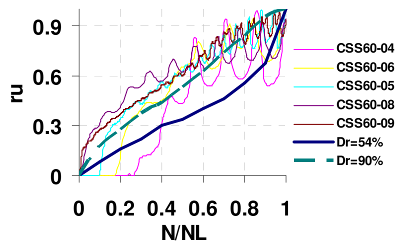

Figure 4 Comparison Between the Data Obtained from the Test and the Results of Calculation

As shown in the Figure 4, test data are reasonably confirmed with the boundaries proposed by Seed et al. [14]. Nevertheless, the middle curve of the tests results have been take into account and it was used for the value of $r_u - N/N_L$ diagram.

3.3. Cyclic Stress Ratio versus Cyclic Number Ratio $CSR - N/N_L$

The cyclic strength curve is commonly normalized by the initial effective confining pressure. This normalized cyclic stress is called the Cyclic Stress Ratio or *CSR*. The *CSR* is defined in various types of tests. For the cyclic simple shear test, the CSR is defined as the ratio of the cyclic shear stress over the initial vertical effective pressure. To plot the diagram of $CSR - N/N_L$ it is needed to acquire the *CSR*.

The data of the undrained cyclic simple shear test on Nevada 40% Sand conducted under 80kPa confining pressure has been utilized and the following diagram has been obtained from the test results. As shown in this Figure, the increment of cyclic number causes decline of CSR.

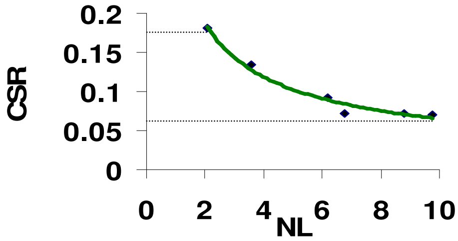

Figure5 Diagram of the $CSR - N/N_L$ for the Simple Shear Test

With achieving the parameters needed to model the centrifuge test, in the next section the results of Numerical Modeling of VELACS centrifuge model #1 test with GEOSLOPE, the equivalent linear total stress, and FLAC, the non-linear effective stress based programs are compared.

4- COMPARISON OF THE RESULTS

The comparison between the values of excess pore water pressure obtained from the numerical implemented models and the data of VELACS project are shown in Figure 6. In addition the results of the hysteresis loop obtained from the various numerical models are shown in Figure 7.

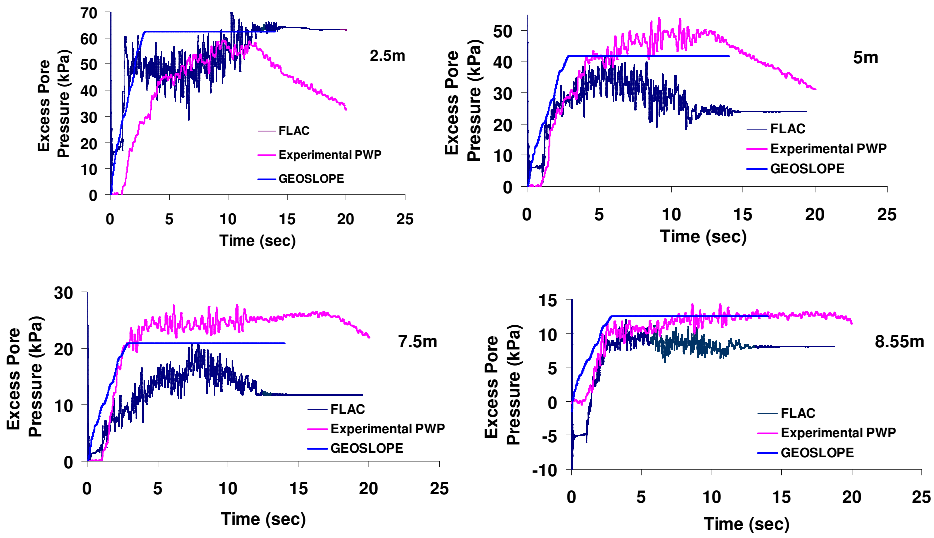

Figure 6 Comparison of Excess Pore Water Pressure Between VELACS Data and Numerical Implemented Models

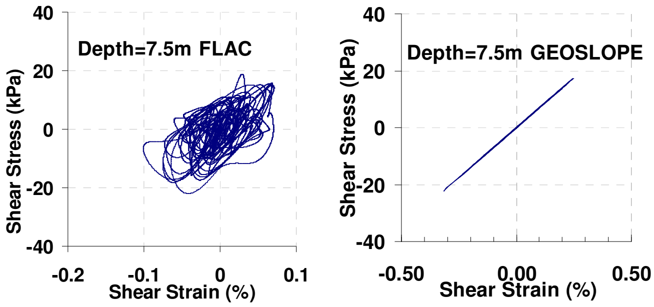

Figure 7 Comparison of Hysteresis Loops Between Numerical Implemented Models

The comparison between the numerical implemented models and the VELACS laboratory data shows that the results of the effective stress method do not match to the test data, and the data of the total stress technique can predict somewhat better results. Although the results of the total stress method seems to be in a general agreement with the laboratory test data, the effects of the pore water pressure are not influenced in shear strain history and calculation of the hysteresis loops are uncoupled. Therefore it can not simulate actual deformations of soils during earthquake in spite of reasonable prediction of EPWP.

5-CONCLUSION

The two different total stress and effective stress approaches were investigated for assessing the generation of excess pore water pressure in the undrained sandy soil during cyclic loading. For this aim, the centrifuge model#1 test conducted in the VELACS project was modeled with numerical programs. The first software was FLAC, non-linear effective stress based computational software, and the second was GEOSLOPE, the equivalent linear total stress approach.

The major deficiency of the total stress method in comparison with the effective stress method is that it is unable to take in to account the progressive stiffness degradation caused by the increase in pore pressure in the soil. In other hand GEOSLOPE is based on the uncoupled analyses in which this software did not concern the existence of pore pressure on the calculation of the shear strain. So, while the equivalent linear approach allows the most important effects of nonlinearity, inelastic soil behavior to be approximated, it must be emphasized that it remains a linear method of analysis and the strain-compatible shear modulus and damping ratio remain constant throughout the duration of an earthquake when the strains induced in the soil are small and large, and permanent strains and excess pore water pressures cannot be computed.

The numerical results obtained from the FLAC outputs in comparison with the VELACS data do not agree totally with each other. In contrast from numerical results obtained using GEOSLOPE, it is clear that FLAC makes its shear strain calculation by the coupled analysis. Thus to take into account the fact that the results of excess pore water pressure obtained from FLAC are not completely in agreement with the VELACS project, its output is more acceptable than the GEOSLOPE outcomes.

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