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Numerical simulation of earthquake-induced liquefactions considering the principal stress rotation

Zhe Wang [a,b], Yunming Yang [c,e,*], Hai-Sui Yu [d], Kanthasamy K. Muraleetharan [e]

[a] Department of Civil Engineering, Faculty of Engineering and Design, Lishui University, Lishui 323000, PR China
[b] Department of Civil Engineering, International Doctoral Innovation Centre, University of Nottingham Ningbo, China, Ningbo 315100, PR China
[c] Ningbo New Materials Institute, The University of Nottingham, Ningbo 315042, PR China
[d] School of Civil Engineering, University of Leeds, Leeds LS2 9JT, UK
[e] Civil Engineering and Environmental Science, University of Oklahoma, USA

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ABSTRACT

Dynamic loadings such as earthquake loadings can generate considerable principal stress rotation (PSR) in the saturated soil. The PSR without changes of principal stress magnitudes can generate additional excess pore water pressures and plastic strains, thus accelerating liquefaction in undrained conditions. This paper simulates a centrifuge model test using the fully coupled finite element method considering the PSR. The impact of PSR under the earthquake loading is taken into account by using an elastoplastic soil model developed on the basis of a kinematic hardening soil model with the bounding surface concept. The soil model considers the PSR by treating the stress rate generating the PSR independently. The capability of this soil model is verified by comparing the numerical predictions and experimental results. It also indicates that the PSR impact can not be ignored in predictions of soil liquefaction.

1. Introduction

The soil behavior under earthquake loadings is one of major research areas in both numerical simulations and experimental studies. The loading conditions under earthquakes are quite diverse and complex, but they share a common characteristic in which the soil is subjected to considerable principal stress rotation (PSR). It is important to consider the PSR impact in many types of geotechnical engineering studies under dynamic loadings. Ishihara and Towhata [9] found that the PSR can generate plastic deformations and the non-coaxiality even without a change of principal stress magnitudes. The PSR can also generate excess pore water pressures and plastic strains in undrained conditions. Similar phenomenon is also found by Ishihara and Yamazaki [10], Bhatia et al. [5], Miura et al. [12], Gutierrez et al. [8], etc. It is well established that the additional excess pore water pressure and plastic deformation caused by the PSR from the dynamic loading can accelerate undrained soil liquefaction. Ignoring the PSR impact may lead to unsafe designs.

At present, numerous researches have been carried out to investigate the soil behavior under earthquake loadings. One of the most famous researches is the VELACS project (Verification of Liquefaction Analysis using Centrifuge Studies). It includes a variety of centrifuge model tests and the corresponding numerical simulations in many universities and research institutes [2]. However, Arulanandan et al. [3] claims that the predicted results from these numerical simulations have great variations and errors which may result from different soil models used by different researchers. They also state that the predicted results are largely affected by the computer codes used and it seems that the program with fully coupled governing equations performs the best among all the results. Although several researchers have implemented their soil models into these numerical simulations subsequently [1,16,17], there are few of them considering the PSR effect.

This paper aims to take into account the impact of PSR on the liquefaction in numerical simulations of earthquake loadings by using a well established PSR model and a fully coupled finite element program DYSAC2 [14,15]. This model is developed on the basis of a kinematic hardening model with the bounding surface and critical state concept. The PSR soil model considers the PSR effect by treating the stress rate generating the PSR independently. The model has been validated in single element studies with different types of sand, such as Nevada sand [18], Toyoura sand [19], Leighton Buzzard sand [20], etc. All the results demonstrate that this model can properly simulate the PSR effects in singe element studies. The focus of the paper is on the investigation of PSR impacts on boundary value problems under earthquake loadings. Firstly, the original base model and the modified PSR model will be

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* Corresponding author at: Ningbo New Materials Institute, The University of Nottingham, Ningbo 315042, PR China
E-mail address: ming.yang@nottingham.edu.cn (Y. Yang).

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introduced. Secondly, these two models will be tested in a single element numerical simulation, compared with experimental results with the PSR. Finally, they will be implemented into FEM software to simulate VELACS centrifuge model tests. The Model No 3 of the VELACS project is chosen to be simulated in this investigation and the comparison will be made between the original base model, the modified PSR model, and the experimental results.

2. The original soil model

2.1. Model formulations

A well-established soil model with the bounding surface concept and kinematic hardening is chosen as the base model. It employs the back-stress ratio as the hardening parameter and the state parameter to represent influences of different confining stresses and void ratios on sand behaviors. It also adopts the critical state concept and the principle of phase transformation line. However, it does not give special consideration of the PSR effect. This model will be briefly introduced, and more details about this model can be found in Manzari and Dafalias [13] and Dafalias and Manzari [7]. It should be noted that this study is focused on the impact of PSR, and the simplified version of the above mentioned models is employed to better present the PSR impact. For example, the fabric impact in Dafalias and Manzari [7] is not considered, which can improve simulations otherwise.

The yield function of the model is defined as:

$$f = \left[(\mathbf{s} - p\boldsymbol{\alpha}) : (\mathbf{s} - p\boldsymbol{\alpha})\right]^{1/2} - \sqrt{2/3}\,pm = 0 \tag{1}$$

where $\mathbf{s}$ is the deviatoric stress tensor. p and $\boldsymbol{\alpha}$ are the confining pressure and back-stress ratio tensor, respectively. $\boldsymbol{\alpha}$ represents the center of yield surface in the stress ratio space while m is the radius of yield surface. m is assumed to be a small constant, indicating no isotropic hardening. The normal to the yield surface is defined as:

$$\mathbf{l} = \frac{\partial f}{\partial \boldsymbol{\sigma}} = \mathbf{n} - \frac{1}{3}(\mathbf{n} : \mathbf{r})\mathbf{I}; \mathbf{n} = \frac{\mathbf{r} - \boldsymbol{\alpha}}{\sqrt{2/3}\,m} \tag{2}$$

where $\mathbf{I}$ is the isotropic tensor and $\mathbf{n}$ represents the normal to the yield surface on the deviatoric plane. $\mathbf{r}$ represents the stress ratio, and is equal to $\mathbf{s}/p$. The elastic deviatoric strain rate $d\mathbf{e}^e$ and volumetric strain rate $d\varepsilon_v^e$ are defined as:

$$d\mathbf{e}^e = d\mathbf{s}/2G \tag{3}$$

$$d\varepsilon_v^e = dp/K \tag{4}$$

where G and K are the elastic shear module and bulk module, respectively, which are expressed as:

$$G = G_0 p_{at}[(2.97 - e)^2/(1 + e)](p/p_{at})^{1/2} \tag{5}$$

$$K = 2(1 + \nu)G/3(1 - 2\nu) \tag{6}$$

where G_0 is a constant, p_{at} is the atmospheric pressure, e is the void ratio, and ν is the Poisson's ratio. The plastic strain rate $d\boldsymbol{\varepsilon}^p$ is defined as:

$$d\boldsymbol{\varepsilon}^p = \langle L \rangle\, \mathbf{R} \tag{7}$$

$$L = \frac{1}{K_p}\left(\frac{\partial f}{\partial \boldsymbol{\sigma}}\right): d\boldsymbol{\sigma} \tag{8}$$

$$\mathbf{R} = \mathbf{n} + \frac{1}{3}D\,\mathbf{I} \tag{9}$$

where L represents the loading index, and $\mathbf{R}$ is the normal to the potential surface, indicating the direction of the plastic strain rate. K_p is the plastic modulus, and D is the dilatancy ratio and they are defined as:

$$K_p = \frac{2}{3}p\left[G_0 h_0(1 - c_h e)\left(\frac{p}{p_{at}}\right)^{-1/2}\right]\left[\frac{|\mathbf{b}: \mathbf{n}|}{|(\boldsymbol{\alpha} - \boldsymbol{\alpha}_{in}): \mathbf{n}|}\right] \tag{10}$$

$$D = A_d \mathbf{d}: \mathbf{n} \tag{11}$$

where $\mathbf{b}$ and $\mathbf{d}$ are the distances between the current back-stress ratio tensor and bounding and dilatancy back-stress ratio tensors, respectively. h_0, c_h and A_d are the model parameters. $\boldsymbol{\alpha}_{\mathbf{in}}$ is the initial value of $\boldsymbol{\alpha}$ at the start of a new loading process and is updated when the denominator becomes negative. In some extreme cases, for example, when the void ratio is very large, K_p can become negative. In that case, care should be exercised to prevent K_p from becoming zero.

2.2. Calibration and model simulations of laboratory experiments

The sand used in Model No 3 test of VELACS is Nevada sand which has a specific gravity of 2.67. Its maximum and minimum void ratios are 0.887 and 0.511, respectively. All the model parameters in both the original model and the modified model are calibrated by a series of triaxial, torsional and rotational tests for Nevada sand from Chen and Kutter [6]. While the triaxial tests do not have the PSR, the latter two tests have the PSR. The stress paths of the torsional and rotational tests are illustrated in Fig. 1. The set of model parameters listed in Table 1 are used for both the single element and finite element simulations. The critical state parameters e_0, λ_c, ξ and M are determined from the quantities at the end of triaxial tests. c is determined by comparing the critical state stress ratios at triaxial compression and triaxial extension. m for the yield surface is assumed to be $M/100$. Parameters n^b and n^d are determined by using the approach in Li and Dafalias [11]. The parameters h_0, c_h and A_0 can be found by trial and error in curve fitting.

Some typical results are shown in Figs. 2–5. Fig. 2 shows the predicted results of the drained triaxial tests, and they generally fit the test results very well. Figs. 3 and 4 show the predictions of torsional shear tests under different initial conditions. In Fig. 3, it can be seen that the effective confining pressure p' is reduced to about 75 kPa, at which the q-p' stress path shows the butterfly shape and p' stops reducing, and the final p' is much larger than the test result. Meanwhile, as the shear stress continues changing, no dramatic shear strain is observed, which is significantly different from the lab results. Fig. 4 shows similar predictions to those in Fig. 3. Fig. 5 shows the predictions of the rotational test. Its simulation is similar to that in the torsional test, and there is a limited reduction of effective confining pressure and small strains, indicating no occurrence of liquefaction.

Predictions of these tests indicate that the original model is able to predict sand responses without the PSR, but is not capable of considering the PSR impact on liquefaction. This is because the model is not able to simulate the considerable volumetric reduction from the PSR. Especially at a large stress ratio close to the phase transformation line, the model usually gives very small volumetric reduction or even volumetric expansion above the phase transformation line. As a result, it constrains the reduction of effective confining pressure near the phase transformation line