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Numerical Predictions for Centrifuge Model Tests of a Liquefiable Sloping Ground Using a Strain Space Multiple Mechanism Model Based on the Finite Strain Theory

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A R T I C L E I N F O

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A B S T R A C T

This paper presents the results of numerical simulations for dynamic centrifuge model tests of a liquefiable sloping ground performed by various institutions within a framework of Class A, B, and C prediction phases of the LEAP (Liquefaction Experiments and Analysis Project). The simulations are performed by using a strain space multiple mechanism model based on the finite strain theory (including both total and updated Lagrangian formulations), in which both material and geometrical nonlinearity are considered. In the simulation, dynamic response analyses are carried out following self-weight analyses with gravity. The soil parameters of the constitutive model are determined based on the results of laboratory soil tests (e.g., cyclic triaxial tests) and some empirical formulae. The identification process of the parameters is explained in details besides the computational conditions (e.g., geometric modeling, initial and boundary conditions, numerical schemes such as time integration technique). In addition to the numerical results of the Class A prediction using a target input motion, those of the Class B and C predictions using recorded motions in the centrifuge model tests are also presented. Comparison between these predictions and measured results has revealed that the constitutive model parameters for effective stress analyses should be calibrated to well capture the shape and trend of liquefaction resistance curves, and subsequently estimate the damage of soil systems due to liquefaction with higher accuracy.

1. Introduction

Studies on evaluation of liquefaction-induced damage to soil-structure systems during large earthquakes have been developed through both experimental (e.g., laboratory soil test, centrifuge model test) and analytical (e.g., effective stress analysis) methods since 1970s. In particular, constitutive models of soils have been advanced by academic researchers toward the application of numerical simulation in practice since 1990s and effective stress analyses are being used increasingly in seismic design for evaluating the degree of damage to soil-structure systems due to liquefaction. The accuracy of these effective stress analyses is considered to be improving through comparison with experimental results and case histories of damage of urban infrastructures in the past large earthquakes. However, a practical process for validation of the analytical procedures including the applicability of constitutive models has not yet been established, in particular for liquefaction phenomena, as commonly recognized among geotechnical engineering community.

The necessity of validation was pointed out in VELACS project more than twenty years ago [1]. The VELACS project contributed to the development of numerical modeling on liquefiable ground, but it was revealed that there were some difficulties in obtaining reliable data for validation because the laboratory and centrifuge experimental results showed some variation among different facilities, in particular for complicated model tests.

In the same vein as the VELACS project, a new international effort called LEAP (Liquefaction Experiment and Analysis Projects) has been proposed [2–4]. The LEAP is an international research collaboration among universities (researchers) in the US, UK, Japan, China and Taiwan to evaluate the capabilities of constitutive models for liquefaction problems. One of the goals is to validate the capabilities of existing analytical procedures, including constitutive models of soils for liquefaction phenomena by using laboratory experiments and centrifuge model tests [5,6]. As part of LEAP exercises, recently Tobita et al. [7] presented results of numerical (Class A) predictions of centrifuge model tests performed at different facilities in Japan for validation of existing effective stress analysis codes. Although valuable results were obtained, some inconsistency was recognized among the test results at

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different facilities, primarily because model containers (shear-beam type containers) with different size, mass, and friction characteristics were used and each centrifuge has custom earthquake simulation shaker systems. This is why validation of numerical models remains a problem yet to be solved because there were some complexities in replicating the experimental boundary condition (i.e., shear-beam type) and properly considering the effects of mass and friction of the shear-beam in simulation.

For LEAP-GWU-2015, one project within LEAP, a new validation effort with simpler boundary condition using a simpler model container has been carried out in order to circumvent the difficulties in numerical modeling associated with complex boundary conditions, and to obtain a set of reliable centrifuge test data with high quality among different centrifuge facilities, which can be used for validation of analytical procedures for liquefaction phenomena. Kutter et al. [8] presents model specifications and compare the results of the centrifuge model tests performed at Cambridge University (CU) in UK, Kyoto University (KU) in Japan, National Central University (NCU) in Taiwan, Rensselaer Polytechnic Institute (RPI) and University of California Davis (UCD) in USA, and Zhejiang University (ZU) in China.

This paper presents results of numerical simulations for the dynamic centrifuge model tests, performed at the six centrifuge facilities, within a framework of Class A, B, and C prediction (e.g., [9]) phases of the LEAP. The simulations are performed by using a strain space multiple mechanism model based on the finite strain theory (including both total and updated Lagrangian formulations) [10], in which both material and geometrical nonlinearity are considered. In this paper, the identification process of model parameters is explained in details besides the computational conditions (e.g., geometric modeling, initial and boundary conditions). In addition to the numerical results of the Class A prediction using a target input motion, those of the Class B and C predictions with recorded motions obtained in the centrifuge model tests are also presented.

2. Brief summary of centrifuge experiments

This section briefly describes model specifications of the centrifuge experiments. The model is composed of uniform sand, with a 5° slope, for all six centrifuge facilities as shown in Fig. 1. For some facilities in which horizontal shaking is carried out in the plane of spinning of the centrifuge, the 5° slope in the shaking direction is modeled as a curved surface corresponding to the radius from the axis of rotation of the centrifuge (Fig. 1(b)). The width of the sloping ground is 20 m and the height at midpoint is 4 m in prototype scale. Fig. 1 also shows the locations of accelerometers (depicted as a rectangle and triangle) and pore pressure transducers (depicted as a circle). Bold solid line symbols indicate required sensors for all centrifuge facilities, highly recommended sensors are shown in bold dashed lines, and recommended sensors are shown in non-bolded solid lines. The sloping ground is made of Ottawa F-65 sand by dry pluviation method with a target density of 1652 kg/m^3, which corresponds to a relative density of about 65%. Following the air pluviation, the ground was prepared to be fully saturated through a number of saturation techniques [8].

A series of five input motions, three of which were non-destructive and two destructive, was used for the LEAP-GWU-2015 validation experiments. All five motions were a ramped sinusoidal wave (1 Hz, 16 cycle) with a specified PGA. Fig. 2 shows the first destructive motion, which is the second motion of the sequence (Motion 2) and used as an input motion for the Class A prediction as described in Section 5, with a PGA of 0.15g. The non-destructive motions (i.e., Motions 1, 3, and 5) were intended to estimate the characteristics (e.g., stiffness) of ground after the destructive motions (i.e., Motions 2 and 4). In the following, the destructive motions are used for validation of the constitutive models of soils and analytical techniques. For further details about the centrifuge experiments, refer to [8].

3. Constitutive model of soils

In this paper, a strain space multiple mechanism model incorporating a new stress-dilatancy relationship [11], which has been extended based on the finite strain theory [10,12], is used as an effective stress model of sands.

The original version of the strain space multiple mechanism model was proposed by Iai et al. [13] within the context of infinitesimal strain theory about twenty years ago. The model has been implemented into a finite element program, called "FLIP ROSE (Finite Element Analysis Program of LIquefaction Process/Response Of Soil-structure Systems during Earthquakes)", and widely used in numerical simulation in practice for evaluating the seismic performance of soil-structure systems [14–16]. In the model, the behavior of granular materials is idealized on the basis of a multitude of virtual simple shear mechanism oriented in arbitrary directions (e.g., the virtual simple shear stress is an intermediate quantity in the upscaling process from the microscopic level to the macroscopic stress). This is why the model can take into account the evolution of induced fabric under various loading conditions, including the rotation of principal stress axis direction, the effect of which is known to play an important role in the cyclic behavior of the anisotropically consolidated sand [17,18].

With an aim to control dilatancy in a more sophisticated manner, the strain space multiple mechanism model has been updated by introducing a new stress-dilatancy relationship [11]. In addition, the model has been recently extended within the context of the finite strain theory [10,12] to take into account the effect of geometrical nonlinearity, and implemented in a finite strain analysis program, called "FLIP TULIP (Finite Element Analysis Program of LIquefaction Process/Total and Updated Lagrangian Program of LIquefaction Process)", which has been developed based on the infinitesimal strain program "FLIP ROSE". The extended model begins to be used in numerical simulation for evaluating the seismic performance of soil-structure systems including large deformation phenomena [19,20].

The finite strain formulation has been derived both in the reference (or undeformed) configuration corresponding to a fixed reference time (i.e., an initial time $t = 0$) and the current (or deformed) one at a subsequent time $t > 0$ [10,12]. The Lagrangian (or material) description based on the former configuration is applied to the total Lagrangian (TL) approach, whereas the Eulerian (or spatial) description based on the latter configuration is used in the updated Lagrangian (UL) approach. The UL approach has advantages in its simplicity in formulation but has disadvantages in that numerical errors in the computed configuration at one time step will be accumulated for the following time steps. The TL approach has advantages in that the computation is always referring to the same reference configuration which is unaffected by the numerical errors but has disadvantages in its complexity in formation. Major advantages in performing both the TL and UL analyses are to confirm the reliability of the numerical results by completely different numerical scheme and formulation. The both types of formulation are available in the program "FLIP TULIP" [10,12].

4. Detailed specification of numerical simulation (FE analysis)

4.1. Definition of Class A, B, and C predictions

In this study, Class B and C predictions are performed besides Class A prediction by using the strain space multiple mechanism model based on the finite strain theory in order to validate the applicability of the model. Preceding a detailed explanation of the analytical condition, the definition of Class A, B, and C predictions are briefly described. According to [9], the meaning of the three predictions is defined as follows: