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Modeling of liquefaction using two-phase FEM with UBC3D-PLM model

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Abstract

Soil liquefaction describes a loss of strength of saturated sand upon sudden or cyclic loading. A slight disturbance of such a soil's fabric might lead to severe damage, e.g. the collapse of sea dikes. Accurate modeling of the state transition between saturated soil and a liquefied soil-water mixture, as well as post-liquefaction phenomena, is crucial for the prediction of such damage. However, developing an appropriate numerical model remains a challenging problem, especially when the simulation involves dynamic large deformation processes. In order to make a first step towards an accurate simulation of soil liquefaction, a two-phase formulation of the finite element method (FEM) in conjunction with the elastoplastic UBC3D-PLM model is investigated. The performance of this approach is analyzed based on a shaking table benchmark.

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1. Introduction

Upon sudden or cyclic loading of loose, fully saturated sands, the pore water pressure can rapidly increase leading to a reduction of the mean effective stress. Liquefaction occurs when a state of zero effective stress is reached, thereby eliminating shear strength. The resulting loss of soil strength can induce substantial damages, such as the failure of earth embankments and retaining structures. For instance, liquefaction in the Hanshin and Awaji island district in Japan in 1995 caused by the Kobe earthquake resulted in widespread lateral displacement of the ground, normal faulting, compression ridges, and the generation of quick sand [1]. The cost of ground failure-related damage to the Port of Kobe is estimated at US$10 billion [2]. A more recent example is severe lateral ground movement in Christchurch (New Zealand) in 2010 and 2011 [3]. Due to the high vulnerability to flooding in low-lying countries such as the Netherlands [4], liquefaction of dike or dune sections poses a serious socio-economic threat.

Accurate modeling of the state transition from saturated soil to a liquid sand-water mixture and post-liquefaction phenomena is necessary for the prediction and possible prevention of damages inflicted by liquefaction. This requires

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a continuum approach capable of capturing the complex two-phase dynamic behaviour of soil during the process of strength reduction. Additionally, the method should be able to accommodate the large deformations of soil in its liquefied state.

In this paper, a two-phase finite element method (FEM) which is a part of the advanced three-dimensional material point method (MPM) software Anura3D [5,6] is considered together with the UBC3D-PLM model developed by Plaxis [7]. The UBC3D-PLM model is a three-dimensional generalization of the widely known two-dimensional UBCSAND model [8–10]. In [11] it is demonstrated that the UBC3D-PLM model has great potential for modeling of liquefaction-related phenomena.

The performance of the proposed approach is examined by applying the numerical model to a shaking table problem that is based on the well-documented case study in [10]. Despite the complexity of the liquefaction process, the considered example can be reduced to a one-dimensional problem. The simplicity and comprehensive description of this benchmark make it perfectly suited for validation and development of the presented approach.

Currently this study does not include large deformations. However, it provides a firm basis for the development of accurate models for soil state transition. To the authors' knowledge, it is also the first attempt to use the UBC3D-PLM model with the FEM featuring a velocity-based two-phase formulation. In future research, the FEM will be replaced by a "two-point" ("double-point") MPM. The MPM introduced in [12] is an appropriate numerical tool for modeling complex large-deformation problems in continuum mechanics. In this method, the material is represented by a set of Lagrangian particles (material points) that move through a fixed Eulerian mesh. The material points carry the physical properties of the continuum such as mass, strain and stress. With the two-point MPM, the soil skeleton and pore water are represented by different sets of particles [13,14]. Therefore, it can be used for the simulation of the relative motion of sand and water, which is essential for modeling post-liquefaction processes such as landslides, flow slides and soil solidification.

The paper is structured as follows. In Section 2, a brief description of the numerical model is provided. In Section 3, the shaking table benchmark is introduced. Moreover, this section gives an overview of the corresponding input parameters and an analytical solution for the linear elastic version of the problem used to design the mesh. The simulation results are discussed in Section 4. In Section 5, conclusions are drawn.

2. Numerical model

Here, the main aspects of the considered numerical approach are described. In the velocity-based, two-phase formulation the velocities of water and solid phase are the principal unknowns. They are computed from the conservation of momentum equations for water and sand-water mixture, respectively. The momentum equations are:

$$\begin{aligned} \rho_w \frac{dv_{w,i}}{dt} &= \frac{\partial p}{\partial x_i} - \rho_w g_i - \frac{n\gamma_w}{k_i}(v_{w,i} - v_{s,i}), \\ (1-n)\rho_s \frac{dv_{s,i}}{dt} &= -n\rho_w \frac{dv_{w,i}}{dt} + \frac{\partial \sigma_{ij}}{\partial x_j} - \rho_{sat} g_i, \end{aligned} \tag{1}$$

where ρ_w is the water density, $v_{w,i}$ is a component of the velocity vector of the water phase in the i-direction, p is the pore water pressure, g_i is a component of the gravitational acceleration vector in the i-direction, n is the porosity, γ_w is the unit weight of the fluid, k_i is the hydraulic conductivity of soil in the i-direction, $v_{s,i}$ is a component of the velocity vector of the solid phase in the i-direction, ρ_s is the density of the solid phase, σ_{ij} is the total stress tensor, and ρ_{sat} is the saturated density.

For two-phase analysis, the total stress is defined as:

$$\sigma_{ij} = \sigma'_{ij} + p\delta_{ij}, \tag{2}$$

in which σ'_{ij} and δ_{ij} are the effective stress tensor and Kronecker delta, respectively.

The pore pressure rate is then obtained from the storage equation representing the conservation of mass:

$$\frac{\partial p}{\partial t} = \frac{K_w}{n}\left((1-n)\frac{\partial v_{s,i}}{\partial x_i} + n\frac{\partial v_{w,i}}{\partial x_i}\right), \tag{3}$$