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Pore pressure effects in seismic simulation oaf an earth dam

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Abstract

Effective and efficient modeling of soil media is of importance in geotechnical earthquake engineering especially when pore pressure development is considered. Concerning the formulation of the coupled approach, a soil element is presented as a mixture of three constituents – soil grains, water and air in the pores. For the mathematical description of the coupled approach mixture theory is considered including the concept of volume fractions. In application of the model the behavior of an earth dam of a trapezoidal cross section is numerically simulated.

Key words: numerical modelling, multiphase approach, finite elements

Effective and efficient modeling of soil media is of importance in geotechnical earthquake engineering especially when pore pressure development is considered. Concerning the formulation of the coupled approach, a soil element is presented as a mixture of three constituents – soil grains, water and air in the pores. For the mathematical description of the coupled approach mixture theory is considered including the concept of volume fractions. In application of the model the behavior of an earth dam of a trapezoidal cross section is numerically simulated. The simulation is done starting from a specified initial degree of water saturation in the dam body. The simulation considers a nonlinear behavior with respect to the water retention curves and material model for the solid state. The air pressure is assumed to stay atmospheric in the course of the calculation and matric suction is equal to a negative value of the hydrostatic stress in water pressure. The coupled model allows to take into account the deformations of the soil skeleton and simultaneously considers the pore water pressure change during the earthquake excitation of the earth dam. The distribution of hydrostatic water pressures at steady state conditions is compared with results from literature which prove the correctness of the coupled approach. The seismic behavior of the dam body gives interesting results considering both deformation and pore water pressure development.

In geotechnical problems the geo-materials are considered by taking into account both the mass transport and flux equations. Simulation of such problems using the finite elements includes the full interaction of the pore pressure with the soil skeleton. It is to be stated that these models based on fully coupled formulation require the simultaneous solution of fluid flow equation and equilibrium equations in terms of displacements [1, 2].

In the present work, the analysis of water flow through an earth dam coupled with the mechanical behavior of the soil skeleton is considered. A mathematical framework assuming porous medium in which the voids of the medium are filled with water is considered and the solution of the partial differential equation system is solved using the finite element method [3]. The numerical model involves both momentum and mass balance equations and can be presented as follows:

$$\begin{pmatrix} \mathbf{M} & \mathbf{0} & \mathbf{0} \\ \mathbf{M_w} & \mathbf{0} & \mathbf{0} \\ \mathbf{M_g} & \mathbf{0} & \mathbf{0} \end{pmatrix} \begin{pmatrix} \ddot{\bar{\mathbf{u}}} \\ \mathbf{0} \\ \mathbf{0} \end{pmatrix} + \begin{pmatrix} \mathbf{C} & \mathbf{0} & \mathbf{0} \\ \mathbf{C_{sw}}^{\mathbf{T}} & \mathbf{P_{ww}} & \mathbf{C_{wa}} \\ \mathbf{C_{sa}}^{\mathbf{T}} & \mathbf{C_{aw}} & \mathbf{P_{aa}} \end{pmatrix} \begin{pmatrix} \dot{\bar{\mathbf{u}}} \\ \dot{\bar{\mathbf{p}}}_\mathbf{w} \\ \dot{\bar{\mathbf{p}}}_\mathbf{a} \end{pmatrix} + \begin{pmatrix} \mathbf{K} & -\mathbf{C_{sw}} & -\mathbf{C_{sa}} \\ \mathbf{0} & \mathbf{H_{ww}} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{H_{aa}} \end{pmatrix} \begin{pmatrix} \bar{\mathbf{u}} \\ \bar{\mathbf{p}}_\mathbf{w} \\ \bar{\mathbf{p}}_\mathbf{a} \end{pmatrix} = \begin{pmatrix} \mathbf{f_u} \\ \mathbf{f_w} \\ \mathbf{f_a} \end{pmatrix} \quad (1)$$

The nodal degrees of freedom for displacement, water and air pressure are taken into consideration as **u**, $\mathbf{p_w}$ and $\mathbf{p_a}$. Their first and second time derivative of solid phase complete the system of equations. The different matrices of the system of equations describe different properties of the numerical model. The indices provide information about the nature and function of the matrix, which can be interpreted as follows.

The coupling matrices $\mathbf{C}_{sw}$, $\mathbf{C}_{sa}$ describe the interaction of the solid phase with water and air phases. The mutual influence of the fluids with each are represented by $\mathbf{C}_{wa}$. The compressibility of the various phases and their effects on the entire media is considered by compressibility matrix $\mathbf{P}_{ww}$. The Permeability matrix $\mathbf{H}_{ww}$ on the other hand, concerns the flow behaviour.

The dam body is a compacted earth dam with 52m length and 12 m height as given in the work of Oettl [4]. The steady state simulation of the dam is simulated to compare the results of the newly developed coupled model. A typical conFigure uration and finite element mesh for the dam body is generated as shown in Figure 1.

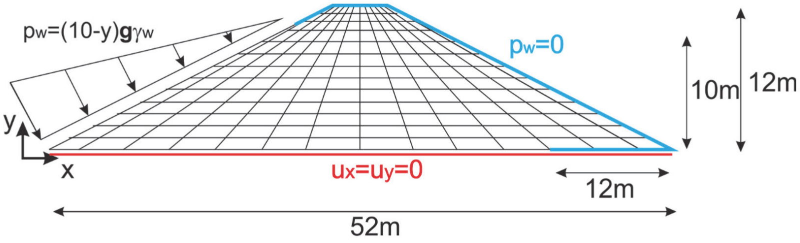

Figure 1. Finite element model of earth dam body

The dam is assumed to be situated above a hard rock formation. The soil material of the dam body is simulated as hypoplastic material model which is nonlinear even for the small deformations. The advantage of this model is that the used hypoplastic model takes into account the accumulation of strain in each cycle of the stress – strain relation [5]. In selection of the material model for solid phase the hypoplasticity material model of Von Wolffersdorff [6] has been used. The material parameters used in the simulations for the dam body are as follows: density of solid phase ρ_s = 2.7 ton/m^3, density of water phase ρ_w = 1.0 ton/m^3, permeability $k = 1.0\cdot10^{-7}$ m/s, compression modulus of solid phase $Ks = 10^9$ kPa, compression modulus of water phase $Kw = 2\cdot10^4$ kPa, dynamic viscosity of water $\mu w = 1.31\cdot10^6$ kNs/m^2, critical internal angle $\varphi c = 30^o$, granulate hardness hs = 1600 MPa, exponent n = 0.39, minimum void ratio e_{d0} = 0.62, critical void ratio e_{c0} = 0.94, maximum void ratio e_{i0} = 1.08,numerical parameters α = 0.2 and β = 1, R = 0.0001, m_r = 2.5, m_t = 9.0, β_r = 0.25, χ = 9.

The base of the dam is assumed to be impermeable and fixed, i.e. the deformability is constrained apart from the drainage which has a length of 12 m. Next, acceleration histories namely, El Centro N-S, USA, 1940, with magnitude M = 6.7, scaled to different peak ground accelerations has been used in order to analyse the behaviour of the dam body under earthquake excitations. The earthquake time histories are used as input accelerations at the base of the dam body for analyses in order to estimate the dynamic response of the dam body under strong earthquakes.

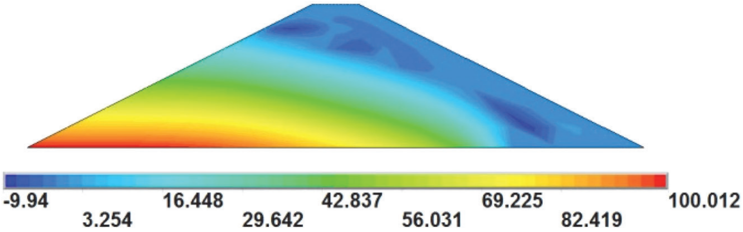

Figure 2. Pore pressure development before applied earthquake acceleration

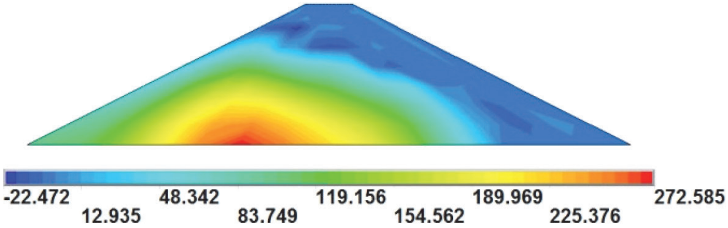

Figure 3. Pore pressure development after applied earthquake acceleration

From Figure 2 and Figure 3 it can be seen that the pore pressure development in the dam occurs in the upfront part of the dam body. The development of the pore pressures directly influences the displacement increase in the dam body which explains the failure mode of earth dams experiencing strong earthquakes. It is to be stated that the earthquake effects have contributed to pore pressure increase especially on the upstream face. The presented coupled approach gains in importance since both pore pressures and deformations are considered simultaneously.

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