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EFFECTS OF CORE STRUCTURE IN MULTIPHASE SIMULATION OF AN EARTH DAM

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Abstract

One of the most popular themes in earthquake geotechnical engineering is the simulation considering the phase interaction among different phases inside the soil medium. The present article aims at providing numerical simulations of an earth fill dam composed of multiphase material models. Moreover, the assessment of liquefaction potential is investigated considering the presence of core structure inside the dam body which obviously has great implications for the results. The formulation of the coupled approach is presented as a mixture of three constituents – soil grains, water and air in the pores.

Mixture theory is considered including the concept of volume fractions in defining of the coupled approach. An earth dam has a trapezoidal cross section with the presence of core structure inside the dam body. The flow of water is different and simulations are more time consuming for which results from literature are used in verification process. The simulation considers a nonlinear behavior with respect to the water retention curves and material model for the solid state. The hydrostatic distribution of water pressured at steady state conditions show obvious differences in saturation of the earth filled dam and are in accordance with the results from literature.

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 usage of hypoplastic model and the accumulation of strain in each cycle of the stress – strain relation makes the model advantageous. Results are compared accordingly, and conclusions provide directions for further usage of the multiphase model in simulation of this type of structures

Keywords: Earth Dam, numerical simulations, multiphase modelling

1. Introduction

Heterogeneous materials and their numerical simulations are of great interest for simulation as a multiphase medium [1-3]. In geotechnical engineering, multiphase modelling has great significance because realistic predictions of soil behaviour can be obtained both in cases of loading and unloading. In simulation of hydro mechanical behaviour of dam bodies, multiphase flow plays an important role in simulation due to the nonlinear nature of fluid flow in pores. In simulating porous mediums such as soil, behaviour is largely driven by the interaction of solid skeleton with water and/or air in the pores. Therefore, the coupled problems of fluid flow and deformation of the solid skeleton are considered in detail. In the description of soil media, different approaches are presented in the literature [4-7]. One of

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the main advantages of using this particular numerical model is that the model can simulate different mechanical properties of porous geo-materials. In this work, the implementation of the numerical model is performed by using the software ANSYS [8].

2. Development of numerical model

In defining porous media, one of the great challenges is to mathematically represent the stages involved. In describing these porous media in the soil, factors such as water saturation and pore pressure have a strong influence on load distribution. In the description of the material, a macroscopic approach was used in which the behaviour of the soil is homogenized (smeared) through a representative volume element. The concept of the volume-share has been used to estimate the participation of each constituent in the formulation of equilibrium equations for each phase and to take into account the interaction between phases. Following the concept of volume fractions, the entire volume consists of a solid fraction *Vs* and a pore volume *Vp*. The pore volume fraction is composed of water and air phases *Vw* and *Va*, respectively as given in Figure 1.

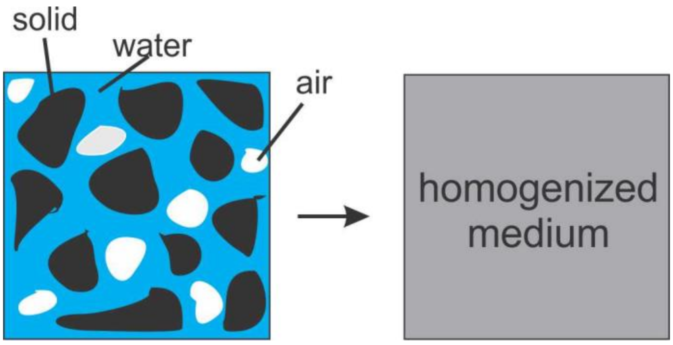

Figure 1. Homogenization of soil medium

In order to include the local composition of the mixture, local volume relations are introduced according to the concept of volume shares. The volume *V* of the total medium arises from the sum of the partial volumes of the constituent bodies.

$$V = \int_B dv = \sum_\alpha V^\alpha \tag{1}$$

The volume shares of solids in relation to the pore volume is given by void ratio n while the proportion of pores sizes are described by void ratio *e*.

$$n = \frac{\text{Pore volume}}{\text{Total volume}} = \frac{V_g + V_w}{V} \tag{2}$$

$$e = \frac{\text{Pore volume}}{\text{Solid volume}} = \frac{V_g + V_w}{V_S} \tag{3}$$

Assuming no mass exchange between phases the balance of mass can be written for each phase as:

$$\frac{d^\pi \rho^\pi}{dt} + \rho^\pi \nabla \cdot \upsilon_\pi = 0 \tag{4}$$

On the other hand, the local form of momentum balance equation for the mixture under quasistatic conditions is given as follows:

$$\nabla \cdot \sigma + \rho g = 0 \tag{5}$$

The capillarity and saturation relationships provide a link between the volume fractions of water and air. Their pressures describe the ability of the soil to store water. The relationship between capillarity and soil saturation depends not only on the properties of the fluid but also on the structure of the porous

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medium. Probably the oldest relationship between capillarity and saturation and still widely used approach was first introduced by Brooks and Corey [9]. On the basis of test results, the capillarity saturation relationship is defined as:

$$S_e = \begin{cases} \left(\dfrac{p_e}{p_c}\right)^{\lambda} & \text{for} \quad p_c \geq p_e \\ 1 & \text{for} \quad p_c < p_e \end{cases} \tag{6}$$

3. Numerical implementation

In this section, the focus is on the implementation of the finite element method of the proposed numerical model in the ANSYS software. Spatial discretization is done by interpolation polynomials (functions of forms). Usually, biquadratic and bilinear approaches are chosen for structural degrees of freedom. The solution of the differential equation is consistent with the physical nonlinearity in the time domain. The total implementation in ANSYS software can be shown as in Figure 2 below:

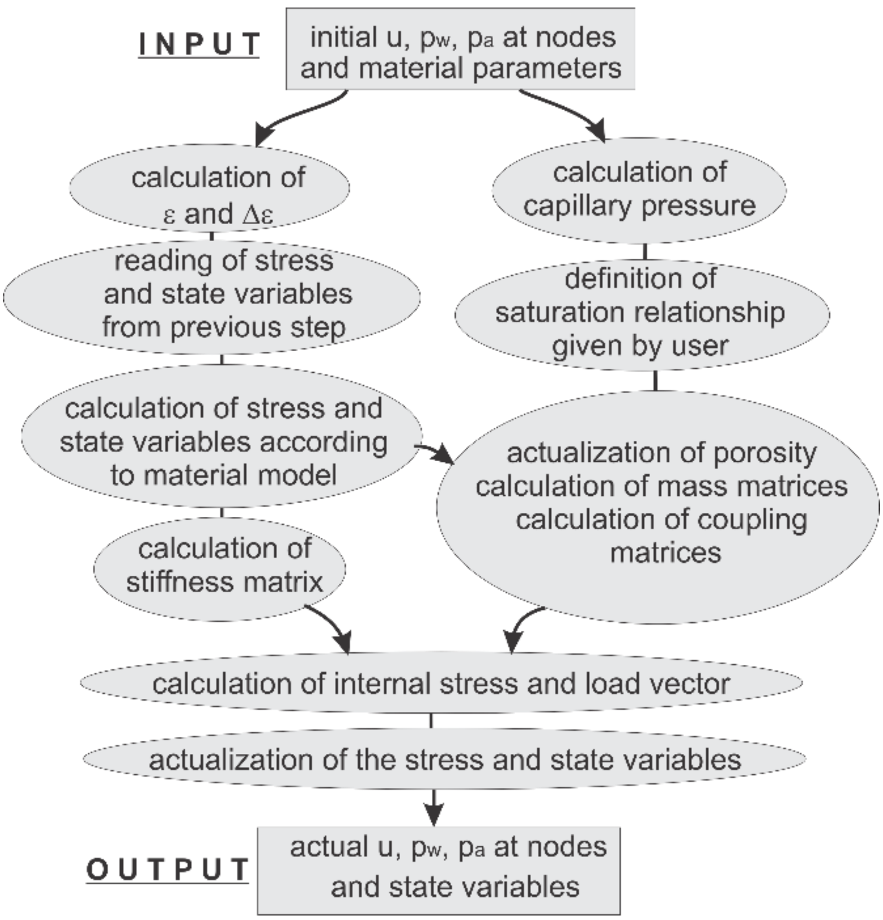

Figure 2. Implementation of the proposed model in ANSYS software

Following the work of first author [2] the finite element equations for the numerical model can be summarized as follows:

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$$\begin{pmatrix} \mathbf{M} & 0 & 0 \\ \mathbf{M_w} & 0 & 0 \\ \mathbf{M_g} & 0 & 0 \end{pmatrix}\begin{pmatrix} \ddot{\mathbf{u}} \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} \mathbf{C} & 0 & 0 \\ \mathbf{C_{sw}}^T & \mathbf{P_{ww}} & \mathbf{C_{wa}} \\ \mathbf{C_{sa}}^T & \mathbf{C_{aw}} & \mathbf{P_{aa}} \end{pmatrix}\begin{pmatrix} \dot{\mathbf{u}} \\ \dot{\bar{\mathbf{p}}}_w \\ \dot{\bar{\mathbf{p}}}_a \end{pmatrix} + \begin{pmatrix} \mathbf{K} & -\mathbf{C_{sw}} & -\mathbf{C_{sa}} \\ 0 & \mathbf{H_{ww}} & 0 \\ 0 & 0 & \mathbf{H_{aa}} \end{pmatrix}\begin{pmatrix} \bar{\mathbf{u}} \\ \bar{\mathbf{p}}_w \\ \bar{\mathbf{p}}_a \end{pmatrix} = \begin{pmatrix} \mathbf{f_u} \\ \mathbf{f_w} \\ \mathbf{f_a} \end{pmatrix} \tag{7}$$

The nodal degrees of freedom for displacement, water and air pressure are taken into consideration as u, p_w and 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 *Csw*, *Csa* describe the interaction of the solid phase with water and air phases. The mutual influence of the fluids with each are represented by *Cwa*. The compressibility of the various phases and their effects on the entire media is considered by compressibility matrix *Pww*. The permeability matrix *Hww* on the other hand, concerns the flow behavior.

4. SIMULATION OF DAM BODY SUBJECTED TO SEISMIC LOADING

This particular example shows the implementation of the proposed numerical model in partially saturated soil medium through a numerical simulation of the dam body given in the work of several authors [1, 7]. The dam body is a compacted earth dam with 52m length and 12 m height. The comparison and verification of the steady state is done in the work of authors [1]. The dam body has a core structure in order to hinder the increase of pore water pressure in case of earthquake excitations. The dam body configuration is shown in Figure 3 below.

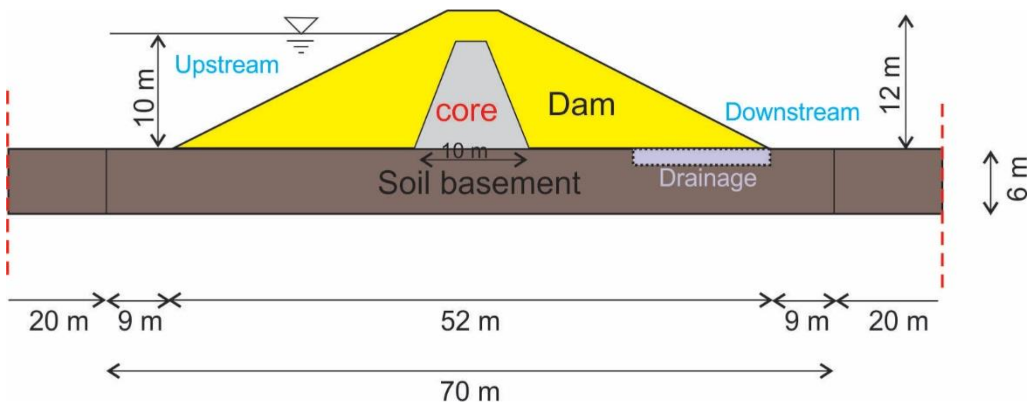

Figure 3. Dam body model with core inside

The dam body is assumed to be situated above a hard rock formation. Therefore, 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 12m. The initial effective stress of the dam is obtained after the seepage analysis and static equilibrium has been reached. As can be seen in Figure 4 the presence of core inside the dam body does not allow the water to flow and thus the pore water pressure is mainly in the upfront part of the dam body.

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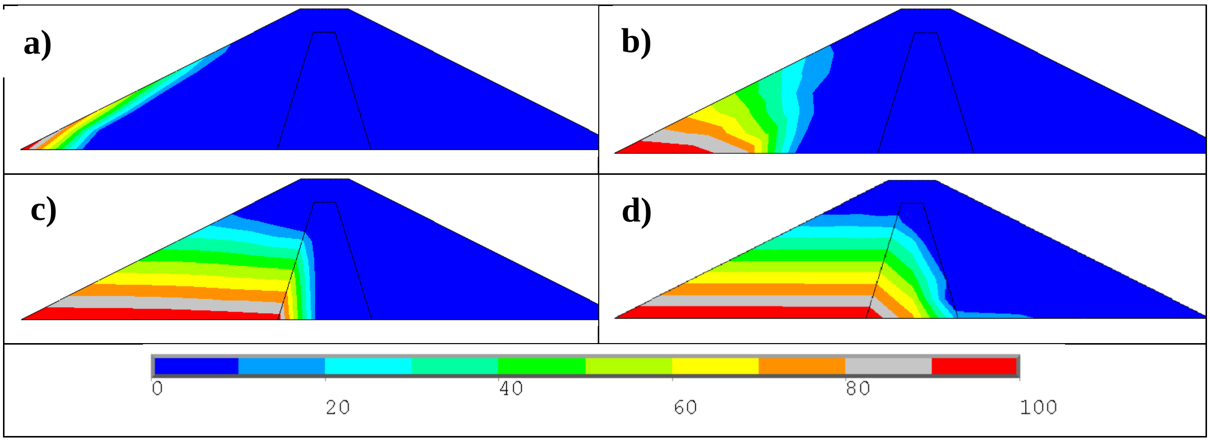

Figure 4. Pore pressure distribution inside the Dam body

On the other hand, the comparison of saturation shows that the presence of core structure inside the dam body has great effects on overall saturation. The saturation distribution inside the dam body is given in Figure 5 below.

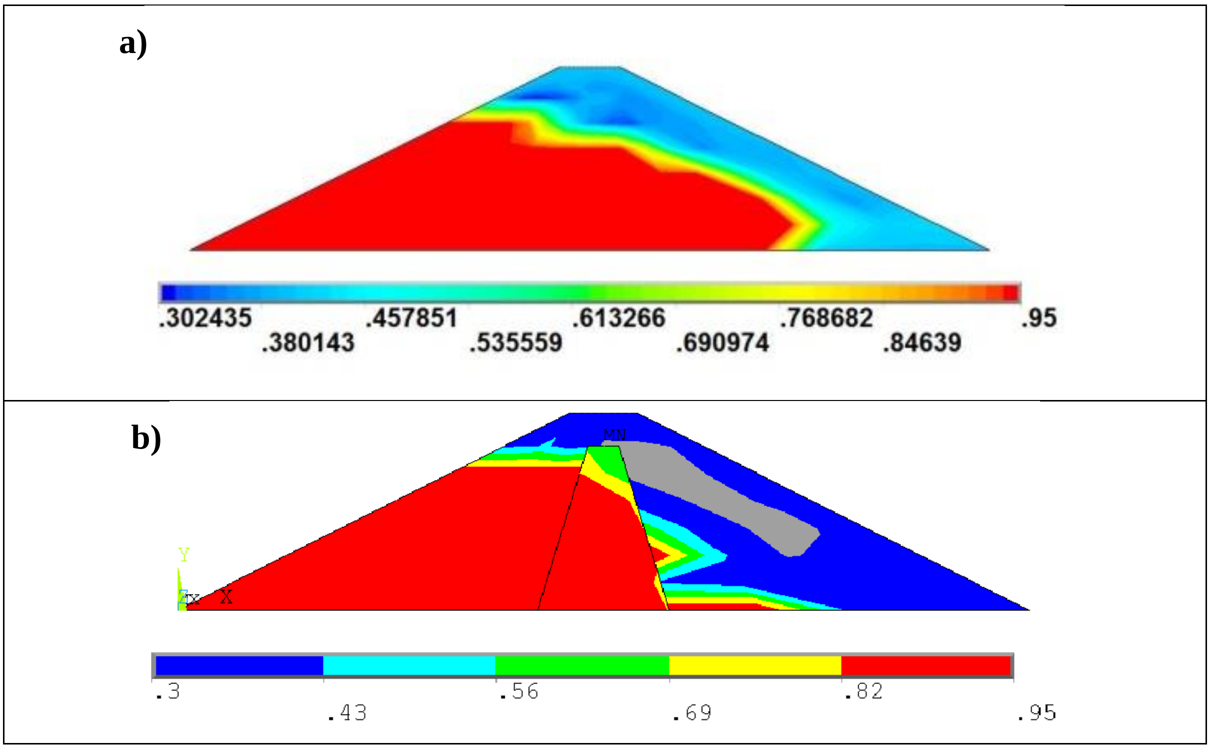

Figure 5. Comparison of saturation distribution

As can be seen from Figure 5, the core structure inside the dam body apart from hindering of saturation, can absorb water with slow permeability since the composition of the core is assumed to be clay.

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5. Earthquake simulations of the dam body

In order to take account of earthquake triggering, three acceleration histories namely, El Centro N-S, USA, 1940, with magnitude M=6.7; Robic N-S, recorded during the Furlania (Italy) earthquake of 15.09.1976 with magnitude M=6.1., Bitola N-S, recorded on 01.09.1994 with magnitude M=5.2-5.4 have been used in order to analyze the behavior of the dam body under earthquake excitations. The input earthquake time histories are scaled to 0.25g and are given in the Figure6 below:

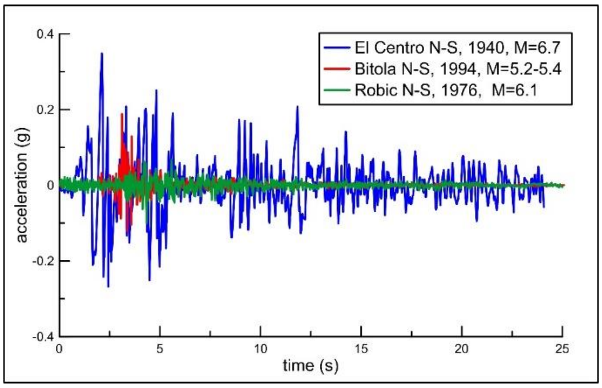

Figure 6. Selected acceleration histories from earthquakes

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. In this paper the numerical results of pore water pressures are simulated and discussed. 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 [10]. In selection of the material model for solid phase the hypoplasticity material model of Von Wolffersdorff [11] has been used. The material parameters used in the simulations for the dam body are as follows: density of solid phase ρ_s=2.7ton/m^3 , density of water phase ρ_w=1.0ton/m^3, permeability k=1.0*10^{-7}m/s, compression modulus of solid phase Ks=10^{9}kPa, compression modulus of water phase Kw=2*10^{4}kPa, dynamic viscosity of water μw=1.31*10^{6}kNs/m^2, critical internal angle φc=30^o, granulate hardness hs=1600MPa, 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. In simulation of earthquake time histories the duration used for simulation is considered only 25seconds during which the peak of accelerations of all earthquake time histories are found. In Figure. 7 the pore water pressure development during earthquake time histories are simulated. The presence of core structure inside the dam body is given with the notion of (core) and comparisons are done consequently.

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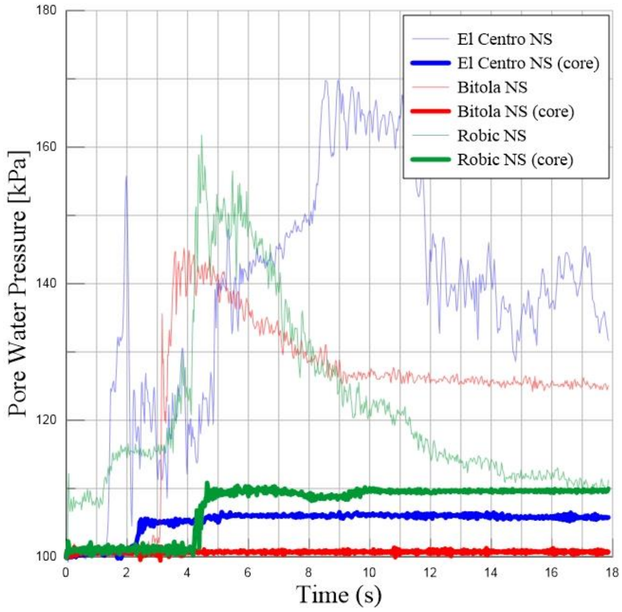

Figure 7. Development of pore water pressure at the top of the dam body

The obtained values in Figure7 are from the upfront part of the dam body in which pore water pressures in cases of dam body and dam body with core structure are compared. As can be seen from Figure 7 the pore pressures in case of earth dam without core structure show increase in values as earthquake time history is applied. On the other hand, the same earthquakes in case of earth dam with core structure does not allow the increase in the pore pressures. However, in the case of Robic NS earthquake time history, the pore pressure tends to increase although the increase is very small in comparison with the pore water pressure in case of dam body without the core structure. In a nutshell, the dam body with the core structure inside, subjected to earthquake excitations triggers very small increase in pore pressures inside the dam body. The increase in the pore water pressures is in the upfront side and is considered to be small in order to initiate any destructive conditions.

6. Conclusions

It should be noted that the presence of core structure inside the dam body contributed to the decrease in pore water pressures which are expected in case of earthquake excitations. Parametric analysis was considered to examine the effects of different acceleration time's histories on the behavior of dam body. In all three earthquakes the increase in pore water pressures in comparison with the case when the core structure is not present, is significantly smaller. The presented coupled approach gains importance because of the detailed presentation of the pore pressures which take place in multiphase medium such as the soil media. The disadvantage of the presented model is the slowness of the computations due to the big size of the included matrices in the calculations.

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