COUPLED APPROACH IN SIMULATION OF 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. 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.

Keywords: numerical modelling, multiphase approach, finite elements

1. INTRODUCTION

In numerical simulation of heterogeneous materials, it is of great interest that the media is simulated as multiphase media (Edip 2013). In geotechnical engineering multiphase modeling has great importance since realistic predictions for the soil’s behavior can be obtained in both loading and unloading cases. In simulation of hydro-mechanical behavior of dam bodies, the multiphase flow plays an important role in simulation owing to the nonlinear nature of the fluid flow in the pores. The simulation of porous media such as soils, the behavior is governed largely by the interaction of the solid skeleton with water and/or air in the pores. Therefore, coupled problems of fluid flow and deformation of solid skeleton are considered in a detailed way.

In describing soil media, various approaches are presented in literature (M.A.Biot 1955; De Boer 1992). One of the main advantages of using this particular numerical model is that the model is able to simulate distinct mechanical properties of the porous geo-materials.

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Simulation of different problems in porous media considering finite elements in time domain has been implemented in literature in the last years (Thigpen and Berryman 1985; Khoei, Azami et al. 2004; Oettl, Stark et al. 2004; Schrefler and Pesavento 2004). Implementation of the numerical model is performed by using the software ANSYS (ANSYS 2006).

2. DEVELOPMENT OF NUMERICAL MODEL

In defining porous media, one of the great difficulties is to mathematically represent the phases involved. In describing these porous soil media, factors like water saturation and pore pressure have a strong impact on the load distribution. In the description of the material, the macroscopic approach has been followed in which the soil behavior is homogenized over a representative volume element. The concept of volume fraction has been used to evaluate the participation of each constituent in formulation of the equilibrium equations for each phase and to take into consideration the interaction among the phases. Following the concept of volume fractions, the entire volume consists of solid fraction $V_s$ and pore volume $V_p$. The pore volume fraction is composed of water and air phases $V_w$ and $V_a$, respectively as given in Figure 1.

![Figure 1. Homogenization of soil medium](image)

In order to account for the local composition of the mixture, local volumetric ratios are introduced according to the concept of volume fractions. The volume $V$ of the overall medium results from the sum of the partial volumes of the constituent bodies (Equation 1).

$$ V = \int_{B} \mathrm{d}V = \sum_{a} V^{a} $$  

(1)

The volume fraction of solids in relation to the pore volume is given by void ratio $n$ (Equation 2) while the proportion of pores sizes are described by void ratio $e$ (Equation 3).

$$ n = \frac{\text{Pore volume}}{\text{Total volume}} = \frac{V_s + V_w}{V} $$  

(2)

$$ e = \frac{\text{Pore volume}}{\text{Solid volume}} = \frac{V_s + V_w}{V_s} $$  

(3)

Assuming no mass exchange between phases the balance of mass can be written for each phase as (Equation 4):
\[
\frac{d}{dt} \rho^z + \rho^z \nabla \cdot \mathbf{v}_z = 0
\]  

(4)

On the other hand, the local form of momentum balance equation for the mixture under quasi static conditions is given as follows (Equation 5):
\[
\nabla \cdot \mathbf{\sigma} + \rho g = 0
\]  

(5)

The capillarity-saturation relationships provide link between the volume fractions of water and air. Their pressures describe the ability of soil to store water. The relationship between the capillarity and saturation of soil depends not only on the fluid properties but also on the structure of the porous medium. Arguably the oldest capillarity-saturation relation and still widely used approach is first presented by the Brooks and Corey (Corey and Brooks 2002). On the basis of test results, the capillarity saturation relationship is defined as (Equation 6):
\[
S_c = \begin{cases} 
\left( \frac{p_c}{p_r} \right)^{\lambda} & \text{for } p_c \geq p_r \\
1 & \text{for } p_c < p_r
\end{cases}
\]  

(6)

3. NUMERICAL IMPLEMENTATION OF THE PROPOSED MODEL

In this part, the focus is given on the finite element method implementation of the proposed numerical model in the software ANSYS. The spatial discretization is performed by means of interpolation polynomials (shape functions). Usually, for the structural degrees of freedom biquadratic and for the pressure degrees of freedom bilinear approaches are selected. The solution of the differential equation is in compliance with the physical nonlinearity in the time domain. The overall implementation in ANSYS software can be shown as in Figure 2 below:
Following the work of first author (Edip 2013) the finite element equations for the numerical model can be summarized as follows (Equation 7):

\[
\begin{bmatrix}
M & 0 & 0 \\
M_w & 0 & 0 \\
M_g & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\ddot{u} \\
\ddot{\dot{p}}_w \\
\ddot{\dot{p}}_a
\end{bmatrix}
+ \begin{bmatrix}
C_{sw} & 0 & 0 \\
C_{wa} & 0 & 0 \\
C_{sa} & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\dot{u} \\
\dot{\dot{p}}_w \\
\dot{\dot{p}}_a
\end{bmatrix}
+ \begin{bmatrix}
\begin{bmatrix}
K -C_{sw} & -C_{sa}
\end{bmatrix} & 0 & 0 \\
0 & H_{ww} & 0 \\
0 & 0 & H_{aa}
\end{bmatrix}
\begin{bmatrix}
\dot{u} \\
\dot{\dot{p}}_w \\
\dot{\dot{p}}_a
\end{bmatrix}
= \begin{bmatrix}
f_u \\
f_w \\
f_a
\end{bmatrix}
\]

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

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 the numerical simulation of the dam body given in the work of Oettl (Oettl, Stark et al. 2004). The dam body is a compacted earth dam with 52m length and 12 m height. The steady state simulation of the dam is simulated to compare the results of the newly developed
coupled model. A typical configuration and finite element mesh for the dam body is generated as shown in Figure 3.

![Figure 3. Finite element model of dam](image)

The dam 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 there is a good correlation between the model simulation of Oettl (Oettl, Stark et al. 2004) and the simulation of this work.

![Figure 4. Comparison of pore pressures (left) and water saturation (right) of Oettl model (a) and the model of this study (b)](image)

In Figure 4 the water saturations and pressure developments follow a good similarity in which it has to be stated that the fully saturated part is hindered at the right side of the base where the drainage prevents the pore pressure development.

Next, 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 behaviour of the dam body under earthquake excitations. The input earthquake time histories are scaled to 0.25g and are given in the Figure 5 below:
Figure 5. 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 the literature, the pore water pressure time histories of dam bodies during earthquakes have been investigated by other authors such as Zienkiewicz (Zienkiewicz, Chan et al. 1990), (Khoei and Mohammadnejad 2011)Khoei etc. In their works, the pore pressure development has caused main issues in the stability of the dam bodies. In this paper the numerical results of both pore pressure and of displacement time history 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 (Niemunis and Herle 1997). In selection of the material model for solid phase the hypoplasticity material model of Von Wolffersdorff (von Wolffersdorff 1996) has been used. The material parameters used in the simulations for the dam body are as follows: density of solid phase $\rho_s=2.7\text{ton/m}^3$, density of water phase $\rho_w=1.0\text{ton/m}^3$, permeability $k=1.0*10^{-7}\text{m/s}$, compression modulus of solid phase $K_s=109\text{kPa}$, compression modulus of water phase $K_w=2*10^4\text{kPa}$, dynamic viscosity of water $\mu_w=1.31*10^6\text{kNs/m}^2$, critical internal angle $\phi_c=30^\circ$, granulate hardness $h_s=1600\text{MPa}$, exponent $n=0.39$, minimum void ratio $e_d=0.62$, critical void ratio $e_c=0.94$, maximum void ratio $e_t=1.08$, numerical parameters $\alpha=0.2$ and $\beta=1$, $R=0.0001$, $m_r=2.5$, $m_t=9.0$, $\beta_r=0.25$, $\chi=9$. 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 6 the pore pressure development during the El Centro earthquake time history simulation is considered. At the beginning the pore pressure distribution is similar to the steady state pore pressure as given in Figure 4. When the peak acceleration is considered at time=5seconds the development of pore pressure intensifies in the middle of the dam body changing the density and effective stress parameters. As the earthquake effects continue the pore pressure development shifts to the left side of the dam body which influences the overall stability of the dam body.
In relation with the pore pressures the displacement values have been considered in Figure 7.
From Figure 7 it can be seen that the calculated displacement vectors follow the pore pressure development in the dam body. As the pore pressures increase the displacement values tend to increase also. As can be seen from Figure 6 and Figure 7 the instabilities appear to be on the front side of the dam. Moreover, the displacement values continue to further increase even after the pore pressure values are ceased. This is due to the fact that the pore pressures have contributed in loosening (de-densifying) of the soil material. As the soil is not dense then the deformations are increased in a continuous manner. In order to compare the deformations of the dam body in Figure 8 comparison is given with other earthquake time histories.

Figure 8. Development of horizontal displacement and pore water pressure at the top of the dam body

The obtained values in Figure 8 are from the upfront part of the dam body in which horizontal displacements and pore water pressures are compared. As can be seen from Figure 8 the pore pressures decrease in the upfront part of the dam body triggers the increase in displacement values in all earthquake time history cases. However, in the case of Bitola and Robic earthquake time histories the pore pressure and horizontal displacements tend to have constant values. This is mainly due to the fact that the input earthquake time histories as given in Figure 5 have low values after the time length of 10 second. In a nutshell, the dam body moves toward upstream permanently only when earthquakes can trigger the increase in pore pressures inside the dam body. In order to consider the potential liquefaction initiation in the dam body, next the excess pore pressure ratio for all earthquake time histories is given.
As can be seen from Figure 9, the ratio between pores pressures and initial effective stresses in all earthquake inputs does not approach the value of unity. In other words, the earthquakes which have been chosen as input accelerations do not trigger liquefaction. Although, the deformations that occur in the presence of increased pore pressures following earthquake loading lead to potential failure and must be considered carefully. As can be seen from Figure 9, the acceleration time history of El Centro increases the most the pore pressure although its effects cause only cyclic mobility allowing big displacements at the top of the dam body.

5. CONCLUSIONS

It is to be stated that the earthquake effects have contributed to pore pressure increase as well as to solid displacements of the dam body, especially on the upstream face. The displacements have been increased significantly after the peak point of earthquake has ended due to a decrease in pore water pressure which contributed to further increase in overall deformation. Parametric analysis has been considered to investigate the effects of different acceleration time histories in the dam body behavior. The presented coupled approach gains in importance since both deformations and pore pressures are considered simultaneously. The results show that the large horizontal permanent movements at the upstream part of the dam body can lead to overall failure of the dam body.

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7. REFERENCES


