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EFFECTS OF GROUND MOTION INTENSITY IN ASSESSMENT OF SOIL SLOPES IN EARTHFILL DAM

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Abstract

The cumulative displacement of sloped soil masses in earth-fill dams subjected to seismic loading is fundamentally governed by both the magnitude and frequency characteristics of the seismic excitation. This correlation necessitates comprehensive numerical simulations incorporating diverse acceleration time histories to capture the full spectrum of potential seismic responses.

This manuscript examines the response of an earth dam slope susceptible to seismically-induced instability under various earthquake scenarios with distinct magnitude-frequency characteristics. The accurate modeling of soil media becomes particularly critical in situations where dynamic pore pressure generation occurs within the soil matrix. The coupled numerical approach developed in this study conceptualizes the soil element as a three-phase medium composed of soil grains, pore water and pore air.

The simulation considers a nonlinear behavior with respect to the water retention curves and material model for the solid state and analysis is performed by ANSYS and PLAXIS. 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. The seismic behavior of the slope gives interesting results considering both deformation and pore water pressure development. The primary objectives of this research are to investigate the seismic response of earth dam slopes under various earthquake scenarios and compare results between ANSYS and PLAXIS software implementations for multiphase soil modeling. The contributions include the development of a comprehensive coupled numerical approach that simultaneously considers soil deformation and pore pressure evolution during seismic loading along with the integration of hypoplastic material model with multiphase flow analysis.

Keywords: Landslide susceptibility, nonlinear modelling, earth-fill dam.

1. Introduction

In the last decades, earthquakes have shown the importance of ground motion intensities in assessment of soil slopes during seismic events. In 1985 a large earthquake with magnitude Mw=8.1 which occurred in Mexican subduction zone proved that the earthquake effects increased in soft soil areas composed mainly of clay layers in the Valley of Mexico [1]. In 2019 during the Durres earthquake with magnitude Mw=6.4 the effects of soil layers played important role in site amplification [2]. The Earthquake in Zagreb, Croatia also showed that the site response amplification should be given importance [3, 4]. In numerical simulation of heterogeneous materials, it is of great interest that the media is simulated as multiphase media [5-7]. In simulation of hydromechanical 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. The advances in computational capabilities have enabled more sophisticated modeling approaches that can better capture the complex interactions between seismic forces, pore pressure development and structural deformation.

2. Model analysis-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. 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 software Plaxis has this module for simulation of multiphase media in a very smooth manner and is widely used. On the other hand, the software ANSYS which is a general FEM software has option for programming a special multiphase element while its procedure is given in Fig. 1.

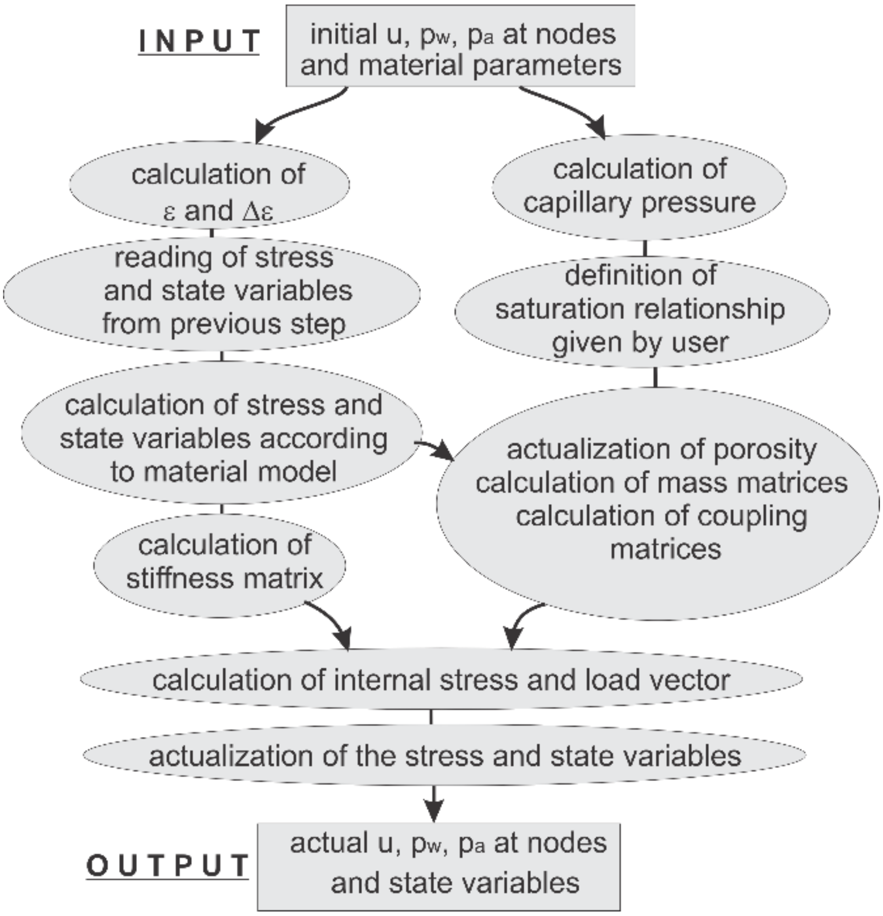


Figure 1. Implementation of the proposed model in ANSYS software [8]

The finite element equations for the numerical model can be summarized as follows:

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

The nodal degrees of freedom for displacement, water and air pressure are taken into consideration as u, pw and pa. 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 behaviour.

On the other hand, the PLAXIS [9] software plays important role in simulation of different problems in geotechnical earthquake engineering. The novelty of the proposed method is that both shear stress in soil and pore water pressures are simulated thus describing the effective stress principle in a correct manner in both softwares. The main novelty is the non-linear material model of hypoplasticity which in both softwares has been added as user advancement for the material modelling.

3. Results in simulation of an Earth Dam slope

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 [10]. The dam body is a compacted earth-fill 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 2.

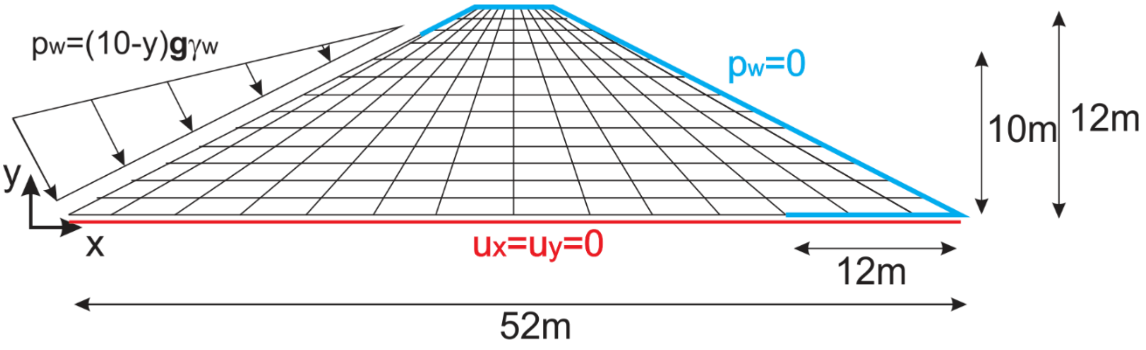
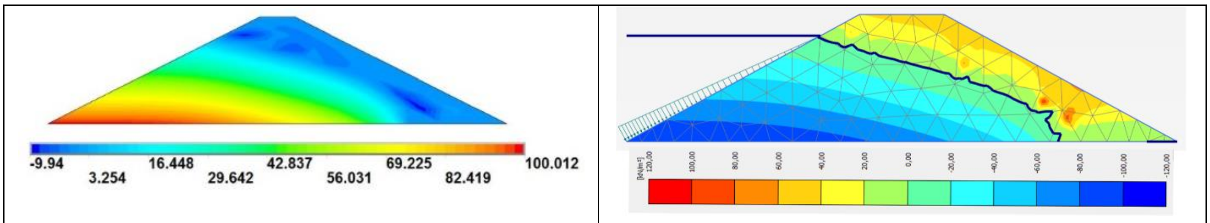


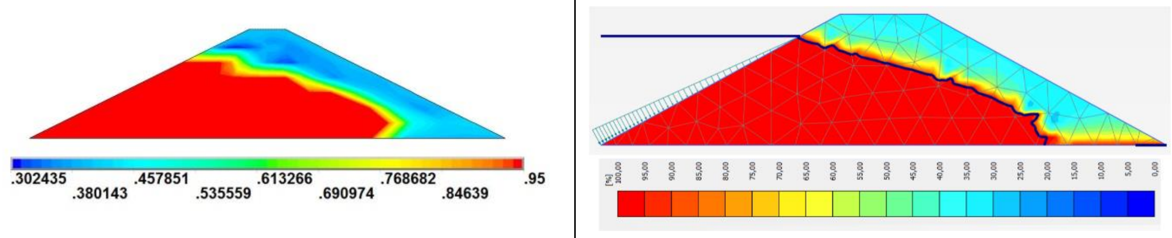
Figure 2. Finite element model of dam

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 ANSYS and PLAXIS.



Pore water pressure generation-ANSYS

Pore water pressure generation-PLAXIS



Water saturation generation-ANSYS

Water saturation generation-PLAXIS

Figure 3. Comparison of pore pressures (left) and water saturation (right) of two softwares ANSYS and PLAXIS

In Figure 3 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 4:

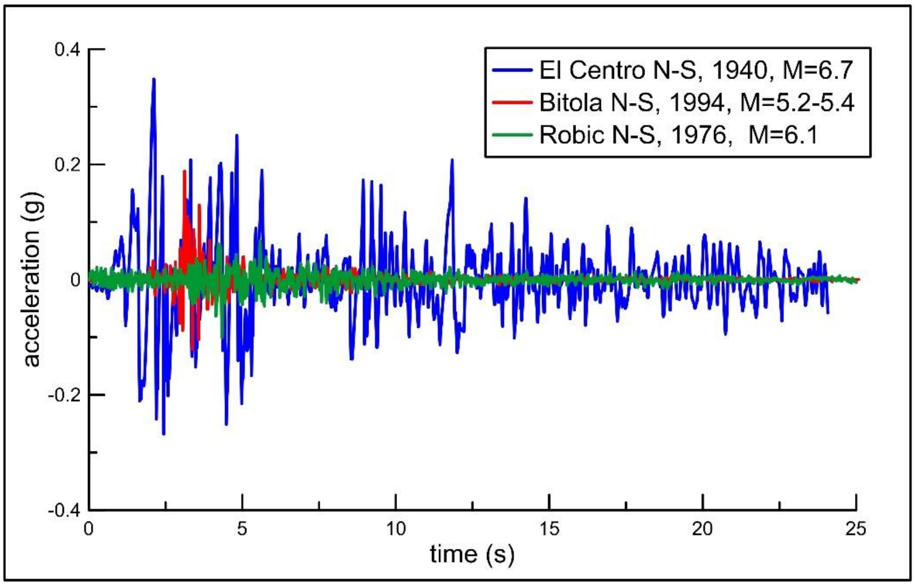


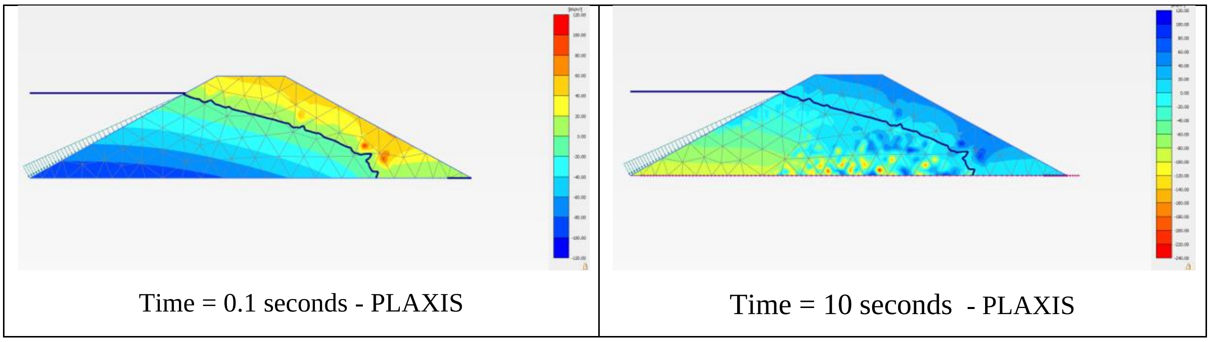
Figure 4. Selected acceleration histories from earthquakes

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 [11], [12], 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 [13]. In selection of the material model for solid phase the hypoplasticity material model has been used.

Table 1. Material parameters of the dam body

	Parameter	**Symbol**	**Value**	**Unit**
1	Density of solid phase	ρs	2.7	ton/m^3
2	Density of water pase	ρw	1.0	ton/m^3
3	Permeability	k	1.0×10^{-7}	m/s
4	Compression modulus of solid phase	Ks	10^9	kPa
5	Compression modulus of water phase	Kw	2×10^4	kPa
6	Dynamic viscosity of water	μw	1.31×10^6	kNs/m^2
7	Critical internal angle	φc	30	degrees
8	Granulate hardness	hs	1600	MPa
9	Exponent	n	0.39	-
10	Minimum void ratio	ed0	0.62	-
11	Critical void ratio	ec0	0.94	-
12	Maximum void ratio	ei0	1.08	-
13	Numerical parameter	α	0.2	-
14	Numerical parameter	β	1.1	-
15	Numerical parameter	R	0.0001	-
16	Numerical parameter	mr	2.5	-
17	Numerical parameter	mt	9.0	-
18	Numerical parameter	βr	0.25	-
19	Numerical parameter	χ	9.0	-

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=10seconds 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.

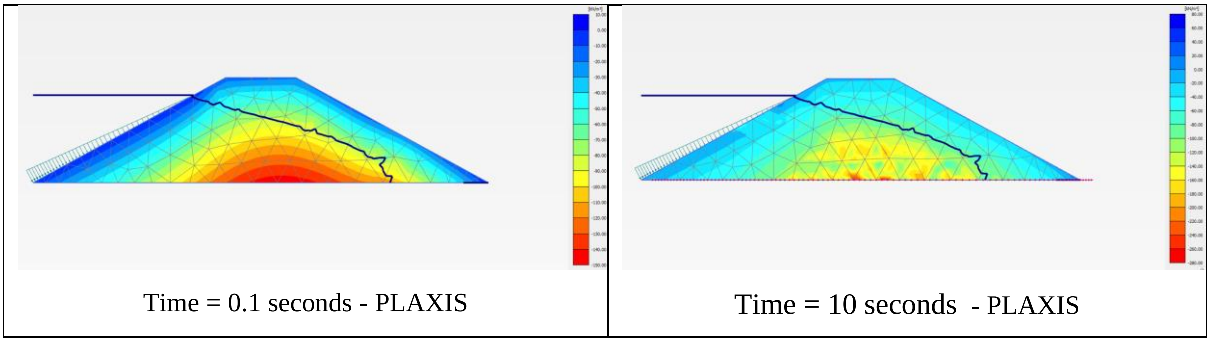


Time = 0.1 seconds - PLAXIS

Time = 10 seconds - PLAXIS

Figure 5. Development of Pore pressure in time

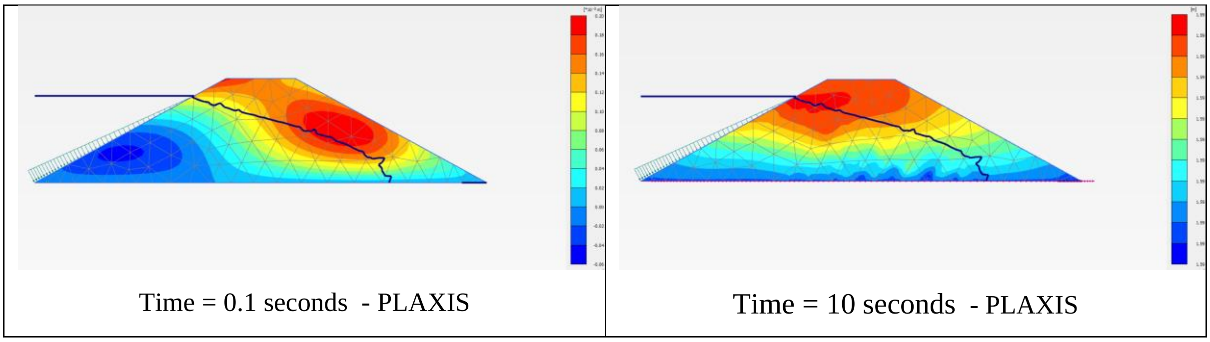
The Figure 6 shows the temporal evolution of pore water pressure distribution in the earth dam. At the beginning of the time the pore pressure is presented as the hydrostatic pressure distribution while at the time=10s, there is notable intensification of the pore pressure development in the central region of the dam body. This intensification is significant because it indicates the change in the density and effective stress parameters according to the Hypoplastic material model which has been used for the soil modelling. The detailed presentation for effective stress is given in Figure 6.


Time = 0.1 seconds - PLAXIS

Time = 10 seconds - PLAXIS

Figure 6. Development of Effective stress in time

As can be seen from Figure 6, the development of effective stress in time during the earthquake simulation follows a gravity induced pattern at the beginning while at the end of time the there is a noteworthy redistribution of effective stresses. This redistribution is directly linked with the pore pressure development as increased pore pressure reduce the effective stress which gives to the multiphase simulation weight in dealing with partially saturated soil media. This reduction in effective stresses is crucial for the stability of the earth dam as it directly affects the shear strength of the soil material.


Time = 0.1 seconds - PLAXIS

Time = 10 seconds - PLAXIS

Figure 7. Development of horizontal displacement in time

Figure 7 shows the development of horizontal displacements in the earth-fill dam body in which at the end of the earthquake loading there is a marked increase in horizontal displacement, particularly pronounced in the upper left portion of the dam body. This pattern of displacement in the dam body correlates directly with the previously observed changes in pore pressure (Figure 5) and effective stress (Figure 6).

The earthquakes applied to ANSYS software reveal similar results in simulation of pore pressures at the upstream slope of the body as given in Figure 8.

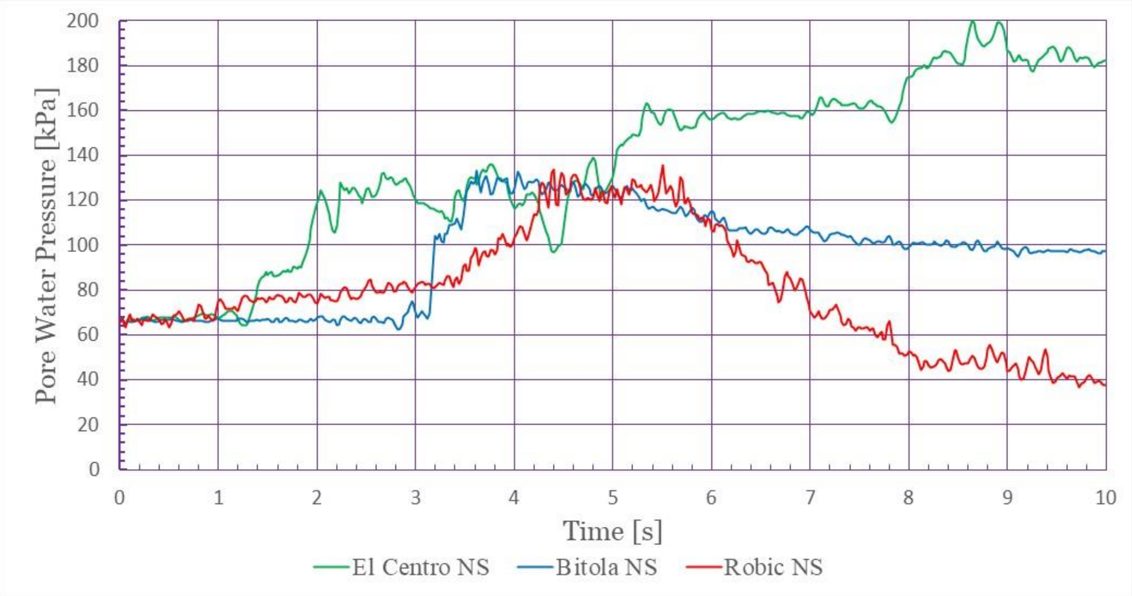


Figure 8. Time history of pore water pressure

As can be seen from Figure 8 the time history of pore pressure developed at the front side of the dam using the software ANSYS has similar forms to those found in PLAXIS above. The observation shows that the increased pore pressure development at the front side (upstream slope) of the dam body correlates with larger displacements which tend to make the dam body unstable. This relationship between pore pressure build-up and horizontal displacement at the upstream slope during seismic loading leads to reduced effective stresses as is also seen in the PLAXIS in Figure6 and should be considered carefully.

4. Conclusions

Based on the analysis of the earth-fill dam's seismic response through simulations using software ANSYS and PLAXIS several significant conclusions can be drawn. The correlation between ANSYS and PLAXIS simulations validates the numerical approaches, demonstrating consistent predictions for both pore pressure distribution and water saturation patterns. It is to be stated that the earthquake loading notably influences both pore pressure development and solid displacements with particularly significant effects observed on the upstream side of the dam body. 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. The parametric analysis examining different acceleration time histories provides comprehensive understanding of dam response under varying seismic conditions. The coupled approach, simultaneously considering deformations and pore pressures proves essential for accurate prediction of dam behavior. Large horizontal permanent movements observed at the upstream side indicate a critical vulnerability zone with potential for triggering overall dam failure. It is recommended to implement enhanced monitoring systems focusing on pore pressure development at the upstream slope and install additional drainage systems to better control pore pressure development during seismic events.

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References

1. Chavez-Garcia, F.J. and P.-Y. Bard, *Site effects in Mexico City eight years after the September 1985 Michoacan earthquakes.* Soil Dynamics and Earthquake Engineering, 1994. **13**(4): p. 229-247.
2. Sheshov, V., et al., *Reconnaissance analysis on buildings damaged during Durres earthquake Mw6. 4, 26 November 2019, Albania: effects to non-structural elements.* Bulletin of Earthquake Engineering, 2021: p. 1-23.
3. Markušić, S., et al., *The Zagreb (Croatia) M5. 5 Earthquake on 22 March 2020.* Geosciences, 2020. **10**(7): p. 252.
4. Atalić, J., et al., *The Mw5. 4 Zagreb (Croatia) earthquake of March 22, 2020: impacts and response.* Bulletin of Earthquake Engineering, 2021. **19**(9): p. 3461-3489.
5. Edip, K., *Development of three phase model with finite and infinite elements for dynamic analysis of soil media*. 2013, Ss. Cyril and Methodius: Institute of Earthquake Engineering and Engineering Seismology.
6. Edip, K., et al., *EFFECTS OF CORE STRUCTURE IN MULTIPHASE SIMULATION OF AN EARTH DAM.* 2023.
7. Edip, K., et al., *Development of coupled numerical model for simulation of multiphase soil.* Computers and Geotechnics, 2018. **96**: p. 118-131.
8. ANSYS. *Fem Software*. 2006.
9. Plaxis, B., *PLAXIS 2D Version 2024-Finite element code for soil and rock analysis.* AA Balkema, Delft, 2024.
10. Oettl, G., R.F. Stark, and G. Hofstetter, *Numerical simulation of geotechnical problems based on a multi-phase finite element approach.* Computers and Geotechnics, 2004. **31**(8): p. 643-664.
11. Zienkiewicz, O.C., et al., *Static and Dynamic Behaviour of Soils: A Rational Approach to Quantitative Solutions. II. Semi-Saturated Problems.* Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences, 1990. **429**(1877): p. 311-321.
12. Khoei, A.R. and T. Mohammadnejad, *Numerical modeling of multiphase fluid flow in deforming porous media: A comparison between two- and three-phase models for seismic analysis of earth and rockfill dams.* Computers and Geotechnics, 2011. **38**(2): p. 142-166.
13. Niemunis, A. and I. Herle, *Hypoplastic model for cohesionless soils with elastic strain range.* Mechanics of Cohesive-frictional Materials, 1997. **2**(4): p. 279-299.