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Performance of nonlinear 2D numerical models for the seismic response of a natural slope

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Abstract

Within the framework of the Spoke 5 "Environment and Natural Disasters" of the National Research Centre in High Performance Computing, Big Data and Quantum Computing, aimed at developing advanced numerical tools for the real-time simulation of natural disaster-inducing phenomena, such as earthquakes and landslides, for reducing the associated risks, the present work illustrates the results of a preliminary numerical investigation conducted to assess the performance of nonlinear 2D finite element (FE) analyses in the evaluation of the seismic response of an ideal natural slope inspired to a real case study. The simulations are performed with the FE code OpenSees and its pre/post processor STKO, taking advantage of the National Research Centre HPC resources to improve their efficiency. The cyclic response of the slope soils is described by the Pressure Independent Multi Yield model, a nonlinear elasto-plastic constitutive law accounting for both isotropic and kinematic hardening. The slope model developed in OpenSees adopts quadrilateral elements implementing the u-p formulation for the solid-fluid interaction during fully coupled dynamic analyses. As benchmark, the same slope is modelled in Plaxis 2D, using the nonlinear elasto-plastic constitutive model HSsmall and a mesh composed by 15-noded triangles. The comparison between the two FE models allows to validate the predictions of OpenSees against a well-established FE software and, more generally, to identify the advantages and limitations of adopting different numerical tools for the assessment of the seismic response of a typical geotechnical boundary value problem.

Keywords: Nonlinear FE modelling; Seismic Response Analyses; HPC; Coupled Dynamic Analysis; Advanced Constitutive Modelling

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1. Introduction

Italy is among the most hazard-prone countries in Europe, facing the highest level of risk from floods and landslides, and is one of the most seismically active regions of the continent. Destructive earthquakes, in addition to causing casualties, have always represented an extraordinary cost that periodically weighs on the economy of the affected areas and directly on public finances. The inherent fragility of the Italian territory, due to its geological and tectonic history, is amplified by the widespread urbanization and the dense network of infrastructures, which significantly increase the country vulnerability and overall risk during natural disaster-inducing phenomena.

The Spoke 5 “Environment and Natural Disasters” of the National Research Centre in High Performance Computing, Big Data and Quantum Computing funded by the National Recovery and Resilience Plan has two main goals: 1) to enhance both the research potential and the efficiency of the scientific community currently engaged in the modelling, simulation and management of natural and anthropic disasters as well as of their effects on the entire ecosystem; 2) to support the society and stakeholders in the definition of disaster risk reduction policies. Within this framework, part of the research activities conducted by the geotechnical group at the Technical University of Bari are dedicated to the advanced modelling of wave propagation processes, including the seismic site response assessment and the analysis of soil-structure interaction problems in dynamic conditions.

Within this framework, the paper illustrates the results of a preliminary numerical investigation conducted to assess the performance of nonlinear 2D finite element (FE) analyses in the evaluation of the seismic response of an ideal natural slope, inspired to the real case study of the western slope of Chieuti (Foggia), in the South of Italy, already investigated by di Lernia et al. (2023). Specifically, two simplified slope models have been developed using OpenSees (McKenna et al., 2000) and Plaxis 2D (Brinkgreve et al., 2022), both characterized by the same ground surface topography and composed by a 50 m thick clay layer overlying the seismic bedrock. The advantage of using OpenSees consists in the possibility to run parallel simulations on HPC systems, thus considerably reducing the calculation time of complex nonlinear geotechnical models. On the contrary, Plaxis 2D is a FE commercial code widely employed in the geotechnical community to study soil dynamic problems and its results can be used as benchmark to validate the predictions of open-source software. The work presented in this paper highlights the advantages and limitations of adopting different numerical tools for the assessment of the seismic response of the ideal natural slope, focusing on the effects of the adopted soil constitutive model on the numerical predictions.

2. Numerical modelling of the ideal slope

The ideal slope model implemented in numerical FE simulations, illustrated in Fig. 1, is characterized by a length of 941.3 m and a maximum height of 170.3 m.

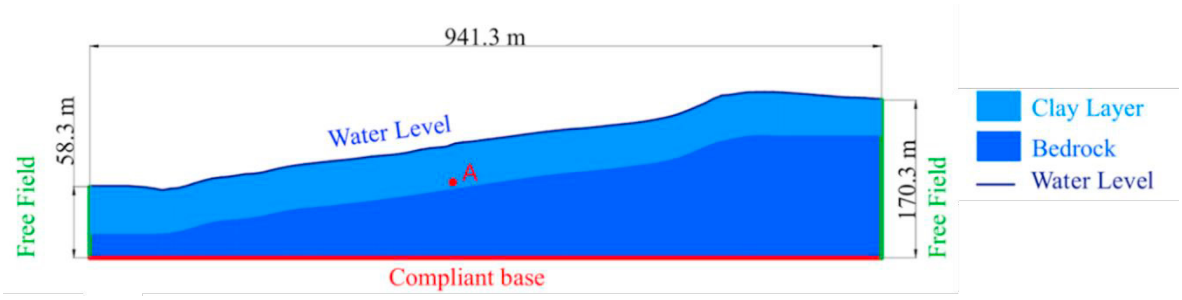

Fig. 1. Ideal slope implemented in numerical simulations and dynamic boundary conditions.

The model consists of a two-layered slope composed of a 50 m thick clay layer with undrained shear strength equal to 270 kPa and a shear wave velocity of 250 m/s, resting on an elastic bedrock characterized by a shear wave velocity equal to 800 m/s. The water level is assumed to be located at ground surface.

The numerical models implemented in the FE codes are reported in Fig. 2. They have been laterally extended by 8 times the height of the lateral side to avoid any interference of the vertical boundaries with the area of interest. The Plaxis 2D model has been discretized with 3157 15-noded triangular elements, for a total number of nodes equal to 26258 (Fig. 2a). Conversely, the OpenSees slope model, shown in Fig. 2b, consists of 37500 4-noded quadrilateral elements with one Gauss point in the center (SSPQuadUP), implementing the u-p formulation for the solid-fluid interaction in dynamic conditions (McGann et al., 2012). These elements have been selected for their numerical stability during elasto-plastic analyses (Cavallo, 2024). The total number of nodes in the OpenSees model is equal to 30974.

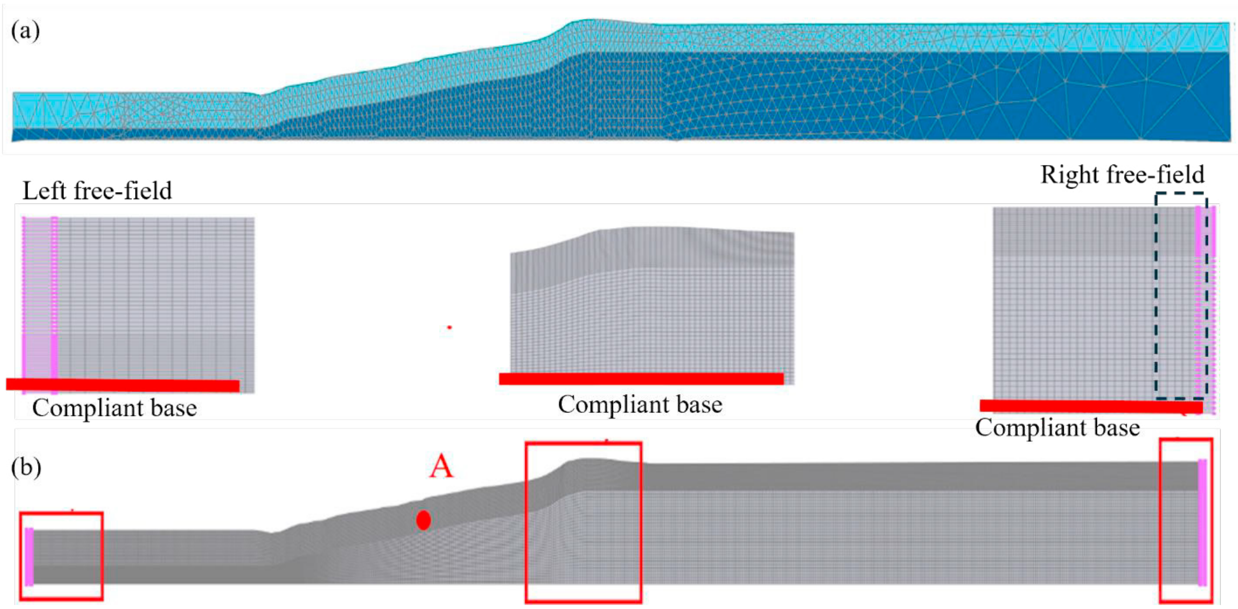

Fig. 2. FE slope model implemented in (a) Plaxis 2D and (b) OpenSees.

The simulations consist of an initial static phase, during which the stress state is initialized through the gravity loading procedure, followed by a dynamic stage. During the static stage, the vertical sides of the model have been restrained in the horizontal direction, while the displacements of the nodes at the bottom have been fixed. In the dynamic phase, free-field boundary conditions have been adopted along the vertical sides, while a compliant base has been imposed at the bottom of the mesh to simulate a deformable bedrock.

In the OpenSees model, the dynamic boundaries have been manually implemented by adding two soil columns internally constrained with tied-nodes and connected to the main geometry with linear dashpots distributed along the vertical edges of the FE model (Cavallo, 2024). During this stage, the static constraints have been deactivated (Løkke et al., 2018), while the entire calculation procedure has been performed using parallel computing with a MUMPS solver. The Newmark time integration method has been employed in dynamic simulations by adopting coefficients $\gamma = 0.5$ and $\beta = 0.25$, which do not provide any numerical damping.

The input motion adopted in the dynamic analyses is represented by the acceleration time history recorded at the Melanico-Santa Croce di Magliano station during the earthquake occurred at Montecilfone (Molise) in August 2018. The seismic motion, characterized by a PGA of 0.022g, has been baseline corrected, filtered to a maximum frequency of 20 Hz and scaled by a factor of 10 to be representative of a strong earthquake (Fig. 3).

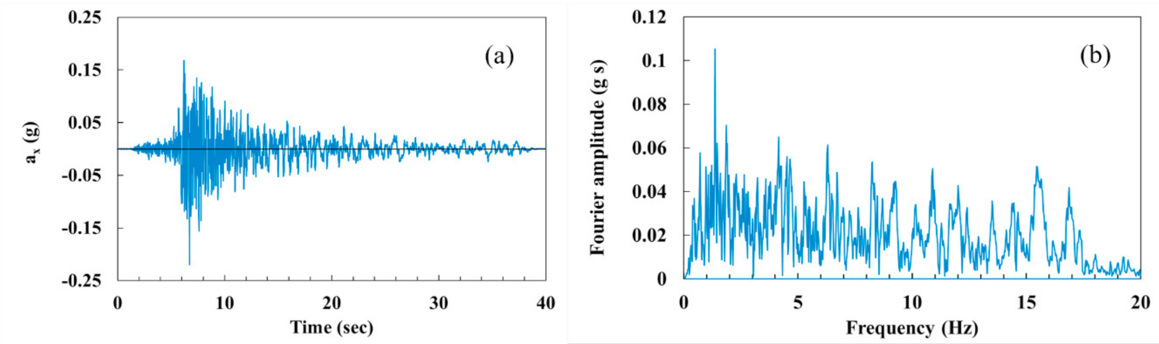

Fig. 3. (a) Acceleration time history and (b) Fourier spectrum of the input motion.

3. Adopted soil constitutive models

The nonlinear response of the clay soil has been described by elasto-plastic constitutive models, while a linear elastic assumption has been adopted to simulate the seismic bedrock response. More specifically, the Pressure Independent Multi-Yield surface constitutive model (named hereafter PIMY, Yang et al., 2008; Qiu et al., 2019) has been adopted in the OpenSees simulation, while the Hardening Soil model with Small Strain Stiffness (HSsmall, Schanz et al., 1999; Benz at al., 2009) has been employed in the Plaxis 2D analysis.

PIMY is a nested surfaces elasto-plastic constitutive law with kinematic hardening. The yield surfaces are of the Von Mises type and plasticity exhibits only in the deviatoric stress-strain response. The stress-strain history of the material can be assigned by imposing the position and dimension of the n-nested surfaces in the deviatoric stress space (Gu et al., 2011). HSsmall, instead, is an isotropic hardening elasto-plastic model, characterized by a volumetric yield surface (i.e. a cap along the isotropic axis) and a deviatoric yield surface which can harden until the Mohr-Coulomb criterion is reached. Changes in the isotropic pressure influence the material shear behavior and the model is able to retains memory of the stress history through the evolution of the cap yield surface. Both constitutive models have been already adopted in the literature to successfully simulate seismic wave propagation processes and the dynamic response of geotechnical structures, such as in Hwang and Rathje (2023) and Amorosi et al. (2016), amongst the others.

The calibration of the PIMY constitutive model parameters has been conducted to reproduce the cyclic response of a clay sample retrieved in Chieuti (di Lernia et al., 2025) obtained through a resonant column test (Fig. 4).

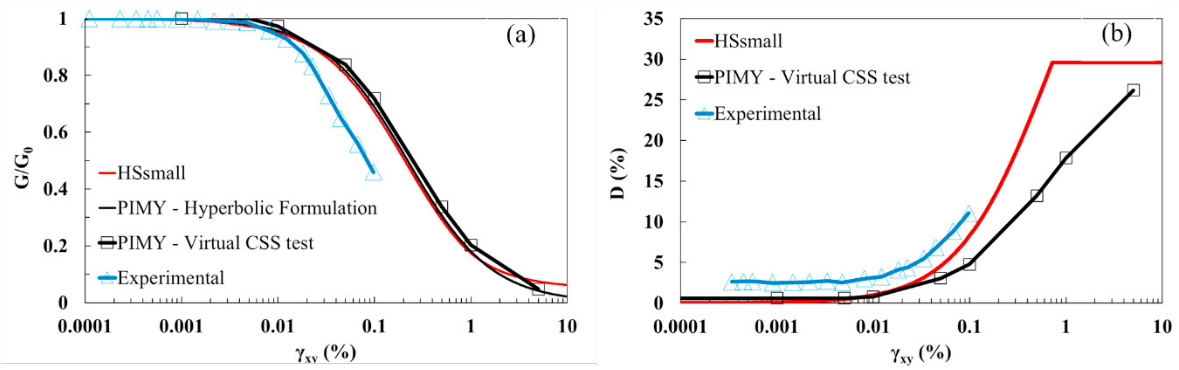

Fig. 4. Comparison between experimental data and (a) shear modulus decay, (b) damping ratio curves obtained with the adopted constitutive models.

Specifically, cyclic simple shear (CSS) strain-controlled tests have been simulated in OpenSees using a single 8-node BrickUP element. The virtual CSS test replicates the initial conditions of the resonant column experiment, characterized by a mean effective stress of 500 kPa, followed by a strain-controlled shear phase conducted by imposing 8 different shear strain values. In this way, the values of the secant shear modulus and the damping ratio have been obtained for each hysteresis loop as a function of the imposed maximum shear strain (Elia et al., 2021; Elia and Rouainia, 2022) and plotted in terms of normalized shear stiffness modulus decay and damping ratio curves to be compared with the experimental data (Fig. 4). It should be noted that the same G/G_0 curve has been obtained directly from the hyperbolic analytical formulation of the PIMY backbone curve. The figure shows that the best possible model calibration provides a stiffer shear modulus decay curve with respect to the experimental data. Indeed, a better matching of the shear modulus decay would have implied the underprediction of the soil undrained shear strength during a monotonic triaxial test performed on the same clay specimen (equal to 270 kPa).

The HSsmall model parameters have been selected to replicate the PIMY cyclic response as shown in the same Fig. 4, in order to enable a direct comparison between the numerical predictions obtained by the two FE codes. The list of the PIMY and HSsmall model parameters is provided in Table 1 and Table 2, respectively.

Table 1. PIMY model parameters.

Parameters	G_{ref} [kPa]	B_{ref} [kPa]	Peak shear strain	n. yield surfaces	p^{ref} [kPa]
Clay Layer	125000	270833	0.1	40	100

Table 2. HSsmall model parameters.

Parameters	G^{ref}_0 [kPa]	G^{ref}_0/G^{ref}_{ur}	G^{ref}_{ur} [kPa]	E^{ref}_{ur} [kPa]	E^{ref}_{50} [kPa]	E^{ref}_{oed} [kPa]	m	p^{ref} [kPa]
Clay Layer	125000	20	6250	16250	3000	8125	0	100

As typically observed for advanced constitutive models, null damping ratio is provided at very small-strain levels by both PIMY and HSsmall model. To overcome this limitation, Rayleigh viscous damping has been implemented in the simulations, by assuming a target value of 3% and 1% for the clay and bedrock layers, respectively, and control frequencies equal to 1 Hz and 10 Hz.

4. Numerical Results

The dynamic elasto-plastic analyses have been performed to evaluate the influence of soil plasticity on the seismic wave propagation in the discretized continuum, considering the different constitutive models implemented in two FE codes. The results of the numerical simulations are illustrated in Fig. 5 in terms of acceleration time histories and corresponding Fourier spectra, shear strain and shear stress time histories, stress-strain curves and variation with time of the excess porewater pressure with reference to point A (ref. to Fig. 1). This point has been selected slightly above the interface between the two layers, 40 m from the ground surface, where the clay elasto-plastic behavior can be clearly detected.

The comparison of the acceleration time histories and the corresponding Fourier spectra (Fig. 5a and b) indicates a good agreement between the two FE predictions, both in terms of amplitude and frequency content. A slight discrepancy might be observed at high frequencies (> 10 Hz), likely to be related to the different finite element mesh characteristics and constitutive models adopted. The shear strain time histories (Fig. 5c) clearly show the great difference in the response of the two constitutive laws. Indeed, the PIMY model tends to exhibit a more pronounced elasto-plastic behavior than the HSsmall model, which reflects in the accumulations of higher plastic deformations. Also, the stress-strain curves (Fig. 5d) show thinner loops of hysteresis predicted by the HSsmall model, indicative of a stiffer and less dissipative response. Conversely, the PIMY model provides more evident accumulation of plastic deformations, which reflects into larger hysteresis loops and associated higher hysteretic damping. It is noted that the kinematic hardening features of the PIMY model imply the exhibition of ratcheting in the dynamic response. This phenomenon, occurring between 6 s and 8 s when the peak of the input motion is reached, is responsible for shifting the stress-strain curves toward negative values of the shear strains, corresponding to the direction of accumulation of permanent displacements in the slope. During the same time interval, a build-up of excess porewater pressures can be observed (Fig 5e). As for the shear strains, a much lower accumulation of porewater pressures is predicted by the HSsmall model implemented in Plaxis 2D.

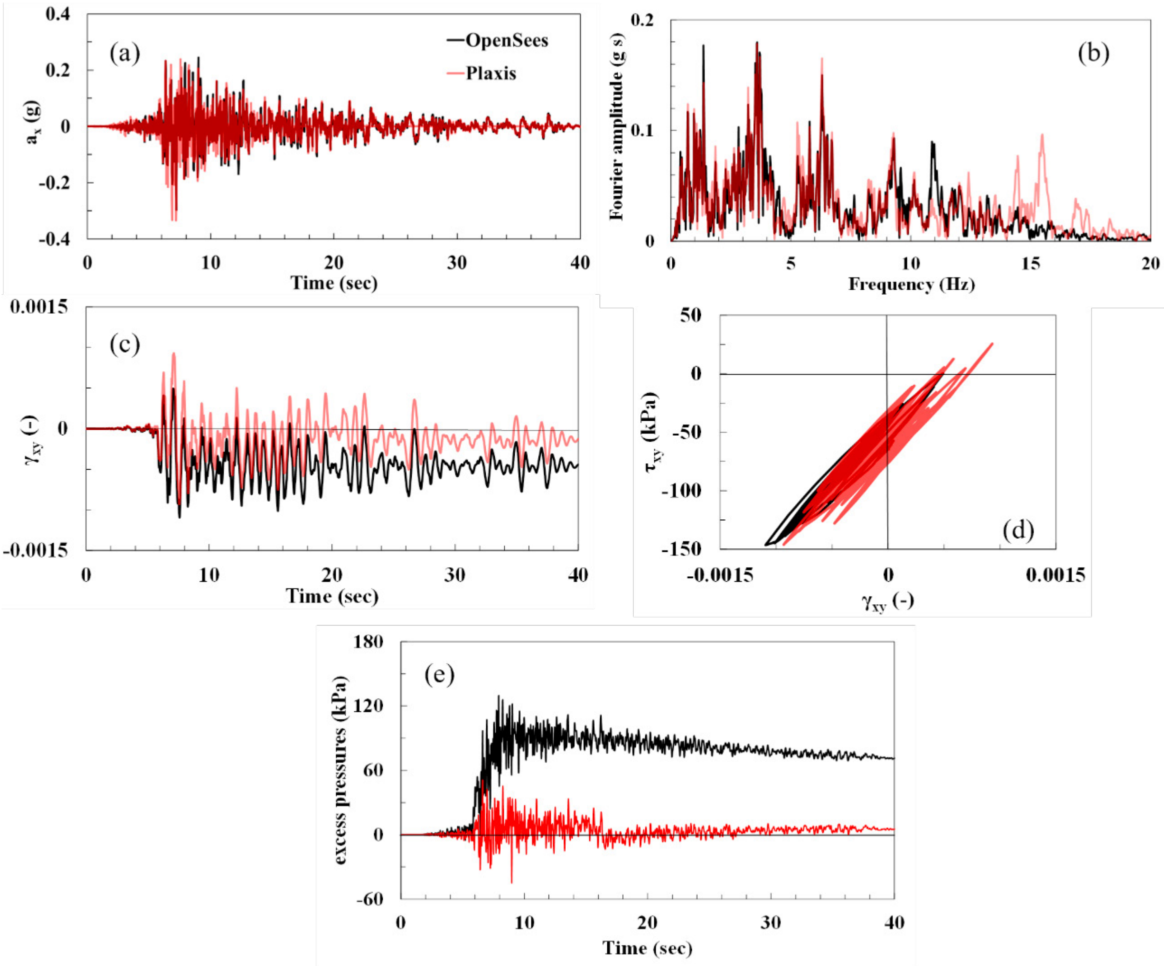

Fig. 5. Comparison between the two FE model predictions in terms of (a) acceleration time histories, (b) Fourier spectra, (c) shear strain time histories, (d) stress-strain curves, (e) excess porewater pressures predicted at point A.

The contours of the horizontal displacements predicted by both FE models at the timeframe of 17.7 s are presented in Fig. 6. A well-defined area characterized by high horizontal displacements accumulated in the slope direction can be recognized in the OpenSees output (Fig. 6a), plotted using PyVista (Sullivan and Kaszynski, 2019). Conversely, the Plaxis 2D model predicts smaller horizontal displacements (Fig. 6b), coherently with the shear strain time history predicted at point A (Fig. 5c).

5. Conclusions

The paper presents the results of a preliminary numerical investigation conducted to assess the performance of nonlinear 2D FE analyses in the assessment of the dynamic response of an ideal natural slope, inspired to the real case study of the western slope of Chieuti, composed by a 50 m thick clay layer overlying the seismic bedrock. Two simplified slope models, with the same ground surface topography, have been developed in OpenSees and Plaxis 2D using similarly refined meshes, same static and dynamic boundary conditions, but different finite element types. To simulate the mechanical behavior of the clay soil, the PIMY and the HSsmall models have been employed in the OpenSees and Plaxis 2D simulations, respectively. They have both been calibrated against the same experimental data to enable a direct comparison between the numerical predictions obtained by the two FE codes.

The comparison of the results indicates a good agreement between the two FE predictions, both in terms of amplitude and frequency content of the accelerations recorded in a selected control point, with a small discrepancy observed at high frequencies. On the contrary, the adoption of a different constitutive model has a higher impact on the prediction of plastic strains induced by the earthquake and associated slope displacements. Indeed, HSsmall seems to exhibit a stiffer and less dissipative response during the cycles imposed by the seismic motion, while PIMY predicts a more diffuse development of plasticity and excess porewater pressures within the clay layer. Nevertheless, the difference between the two models in terms of slope displacements consists of few centimeters only.

In general, the results of the work enable to confidently pursue the use of OpenSees in the analysis of complex nonlinear geotechnical models and to fully exploit in the future the possibility to run parallel simulations of large 3D models on HPC systems with reduced calculation time.

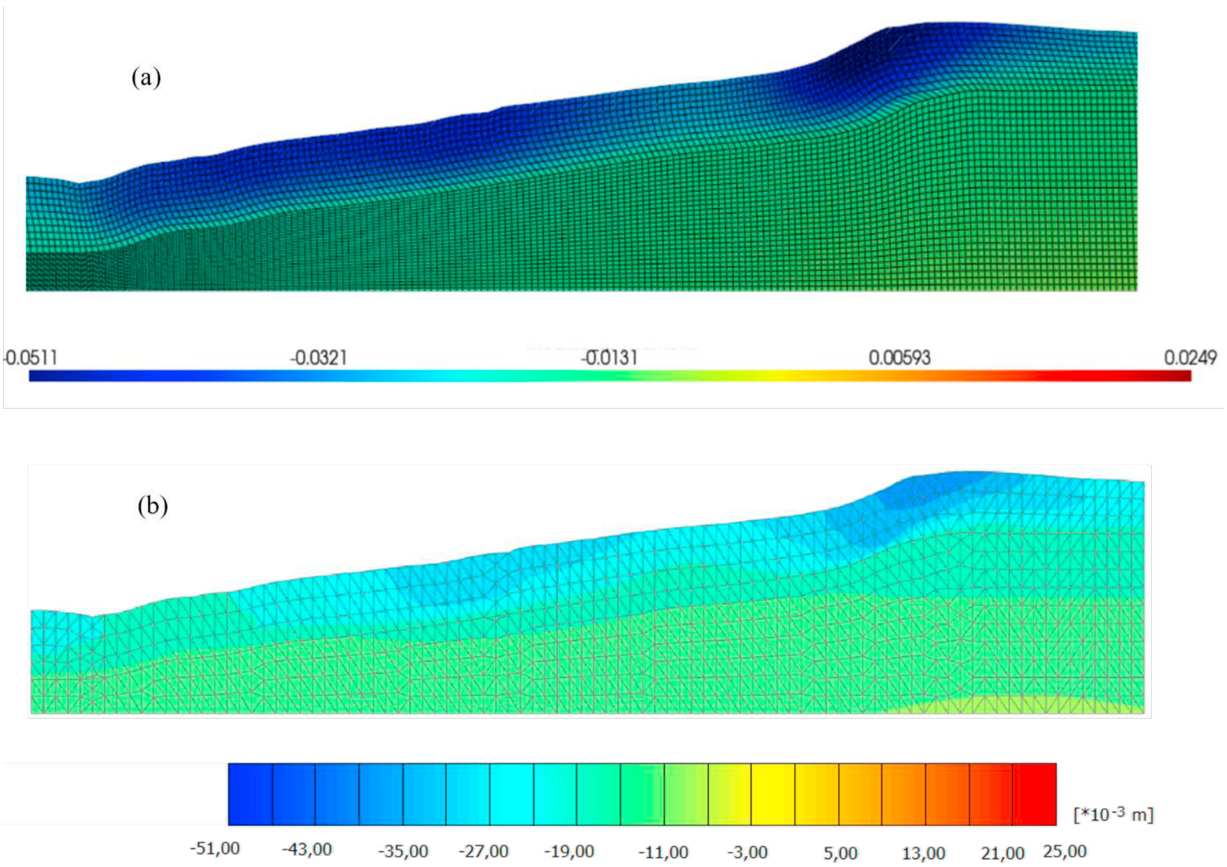

Fig. 6. Horizontal displacement contours predicted by (a) OpenSees and (b) Plaxis 2D model at the timeframe of 17.7 s.

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