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Numerical and physical modelling of the seismic response of gentle slopes in soft clay

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ABSTRACT: This paper presents the development and validation of numerical models designed to simulate the seismic response of gentle slopes in soft clay, a topic of significant interest in the scientific community due to the potential implications for geotechnical engineering and hazard mitigation. The motivation for this research stems from the need to improve the understanding of the behaviour of such slopes under seismic loading, particularly in light of existing research and methodologies. Nonlinear ground response analyses were conducted using OpenSeesPL, incorporating three-dimensional soil columns and a dynamic nonlinear constitutive model. Validation of the numerical models was performed by comparing the results with experimental data obtained from centrifuge tests on gentle slopes. Evaluation criteria included lateral displacements and acceleration-time histories. To conclude, the paper presents the results of simplified parametric analyses, examining the seismic response of gentle slopes at various inclination angles. The findings of this research aim at understanding of the seismic behaviour of such slopes and suggest directions for future research and model refinement. This work also provides reference data sets for numerical simulations and model preparation methodologies, including the use of a laminar container for simulating an infinite slope condition.

1 INTRODUCTION

The study of deep-water continental slopes has gained significant attention in recent years due to the growing offshore energy industry and the development of renewable energy sources. As a result, various offshore geohazards have been identified and defined, with submarine landslides representing a prominent phenomenon worldwide. These landslides can range from large-scale events (Vanneste et al., 2006) to minor instabilities, posing risks to offshore oil and gas operations. Understanding the various geotechnical-geological processes that lead to these hazardous conditions, particularly seismic-induced landslides, is crucial for effective risk assessment and mitigation strategies.

Recognizing the importance of seismic stability in submarine slopes, researchers have made contributions to understand the dynamic behaviour of these slopes and the mechanisms of earthquake-induced deformations (Biscontin et al., 2006). However, despite these advancements, some areas still require further investigation, particularly the seismic response of gentle slopes (with inclination angles from 1° to 5°, according to Masson et al., 2006) under seismic loading.

This paper presents the results of an experimental program conducted at the Federal University of Rio de Janeiro, Brazil, aiming to investigate the seismic response of gentle slopes in clay using a combination of centrifuge testing and numerical modelling. Specifically, this paper focuses on the calibration of numerical models based on centrifuge experiments conducted at the Schofield Centre (University of Cambridge, UK). The performance of these models was evaluated by comparing their results to the experimental data on accelerations and seismic displacements of the slope models.

2 MATERIALS AND METHODS

To calibrate the numerical models, a centrifuge test involving a three-degree gentle slope subjected to earthquake loads was selected. The centrifuge experiment was conducted at the Schofield Centre (University of Cambridge, UK). A laminar model container comprising a series of rectangular frames (laminae) separated by cylindrical bearings, minimizing friction between laminations, was employed for slope model construction (Brennan and Madabhushi, 2006).

The model soil profile was constructed from reconstituted Speswhite kaolin placed in a consolidation container. The initial water content of the kaolin was 120%, representing a slurry condition that facilitated its placement inside a rigid consolidation container. Subsequently, a series of consolidation pressures were applied using computer-controlled consolidation until reaching a pre-consolidation pressure of 250 kPa. This consolidation pressure was defined to obtain a block of clay with enough strength to support the static shear stresses due to inclination during the test. A range of undrained shear strength values between 9 kPa and 27 kPa was obtained for the clay profile (Table 1). Figure 1 shows the setup employed for the consolidation of the clay.

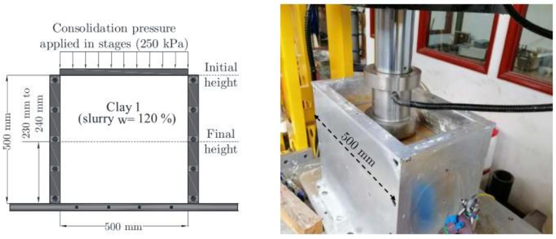

Figure 1. Detail of clay consolidation

Upon completion of consolidation, the consolidation container was dismantled, resulting in a block of consolidated clay as shown in Figure 2.

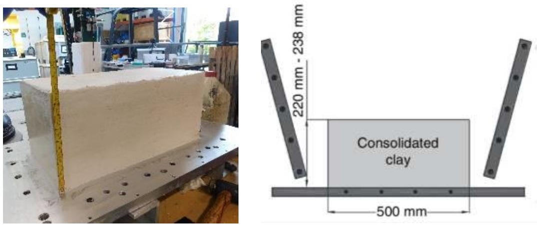

Figure 2. Clay at the end of consolidation

In the sequence, a rubber membrane was installed around the consolidated block of clay and the frames of the laminar container were installed around as depicted in Figure 3.

Figure 2. Setup of laminar model container

The next stage of the model preparation was the installation of the instruments. The model was instrumented with piezoelectric accelerometers (Birchall, type A-23), Linear Variable Differential Transformers (LVDTs type DC15 by Solartron), Druck pore pressure transducers (PPTs), a setup to carry out in-flight t-bar tests and an air hammer device (AHD) to measure shear wave velocities throughout the clay. Detailed information about the model preparation methodology can be found in Soriano et al. (2021). Figure 3 presents the experimental setup of the gentle slope model and Figure 4 provides a general view of the model installed in the centrifuge.

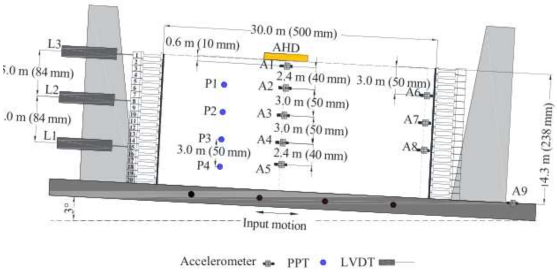

Figure 3. Three-degrees gentle slope model

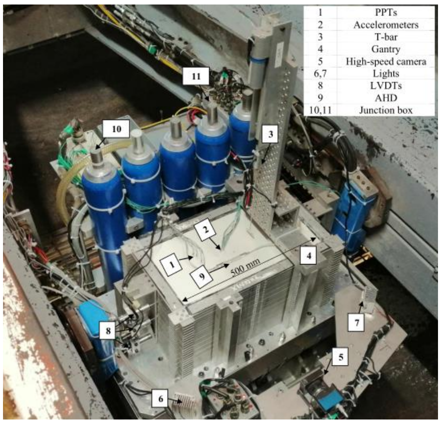

Figure 4. A view of the model installed in the centrifuge

3 CENTRIFUGE TEST

The model was subjected to a set of earthquakes of varying amplitude and frequency content using the servo hydraulic actuator developed by Madabhushi et al., 2012. Figure 5 displays the acceleration-time histories and frequency content of the input motions applied to the model, presented in terms of prototype scale. The experiments were conducted at a g-level of 60-g.

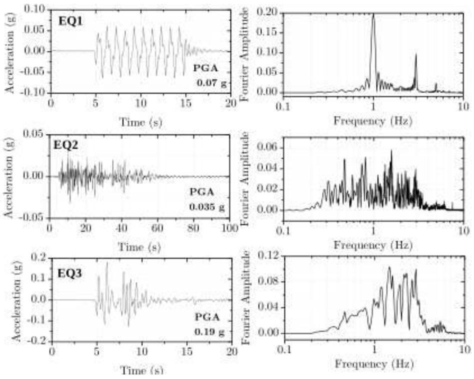

Figure 5. Applied input motions (part 1)

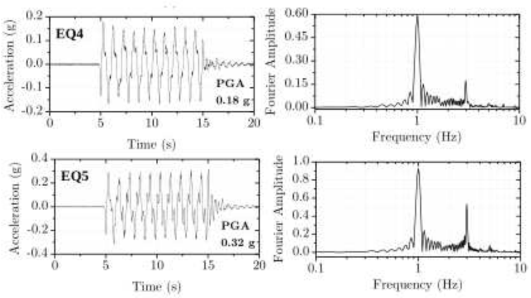

Figure 5. Applied input motions (part 2)

The following are the stages of the experiment:
(i) Pre-flight checks; (ii) Swing up to 60g; (iii) Consolidation for 40 minutes at 60g, followed by an Air Hammer Test (Ghosh and Madabhushi, 2002); (iv) T-bar test; (v) Earthquakes: EQ1, EQ2, EQ3, EQ4, EQ5 ; (vi) Swing down; (vii) Post-test investigations.

4 NUMERICAL MODEL

A series of nonlinear ground response analyses were conducted in to simulate the seismic response of the centrifuge model. Numerical simulations were performed using OpenSeesPL (Elgamal and Yang, 2011), employing a three-dimensional soil column and a dynamic nonlinear constitutive model (Yang and Elgamal, 2003). The performance of the numerical models was evaluated by comparing their predictions of the slope's response in terms of lateral displacements and acceleration-time histories with the measured data from the centrifuge experiment.

4.1 Methodology

Given the characteristics of the problem studied of a gentle slope, the model was simplified, and a soil column was used to simulate the soil profile. For that purpose, a shear beam behaviour with a boundary condition of equal displacement constraints (x, y, and z) for all the nodes at the same depth was adopted. This technique is less time-consuming than a fully 3D approach. Phillips (2012) developed numerical models of soil to simulate free-field lateral spreading centrifuge tests. Taiebat et al., (2010) employed a similar approach to study earthquake-induced shear deformations in gentle slopes. Figure 6 illustrates an example of a soil column used to represent the soil profile. This soil column extends 1.0 meter in both the x- and y-directions. Eight-node brick elements were employed for the analyses, as the simulations were based on total stresses. These elements are based on a trilinear isoparametric formulation and possess three translational degrees of freedom per node. The model was subdivided into layers of 1.0 meter, with each layer divided into four brick elements. This arrangement ensures an adequate number of elements within the wavelength of a shear wave.

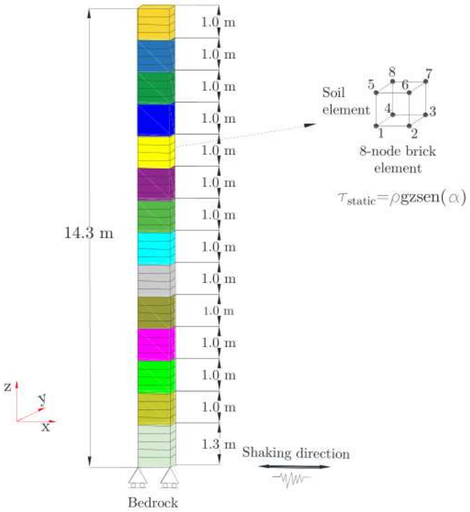

Figure 6. Schematic of a 3D column to simulate a layered slope

4.2 Boundary conditions

In OpenSeesPL, various boundary conditions are available, including Shear Beam, Rigid Box, and Periodic Boundary (Elgamal and Yang, 2011). For this numerical analysis, the Shear Beam condition was selected. The slope inclination was simulated by imposing a static driving shear stress component onto the soil column. This static stress can be expressed as:

$$\tau_{static} = \rho * g * z * sen(\alpha) \qquad (1)$$

Where, ρ is the soil density; g the gravity acceleration (m/s^2); z the model depth (m); α slope inclination angle.

For the application of the earthquake input motions, a rigid bedrock condition was assumed at the bottom boundary. This condition implies that the bottom boundary is fixed horizontally and vertically.

4.3 Soil constitutive model and parameters

To simulate the dynamic response of the clay inside the laminar box, an accurate constitutive model is required. In this analysis the soil constitutive model for the clay is the PressureIndependentMultiYield (PIMY) (Mazzoni et al., 2005).

The PIMY model is an elasto-plastic model. The volumetric strain is linear elastic. The model exhibits plasticity in the deviatoric stress-strain response and is not sensitive to confinement (for example, the undrained behavior of clays). The PIMY material model utilizes nested yield surfaces that allows the control of the plastic modulus, then they can be adjusted to comply with a specified backbone curve.

Table 1 summarizes the parameters employed for the PIMY material model.

Table 1. Soil parameters for PIMY material model

Model parameters	Value
Saturated mass density (Mg/m3)	1.8
Reference pressure (kPa)	100
Pressure dependence coefficient	0
Shear wave velocity (m/s)	65-116*
Peak shear strain	0.1
Friction angle	0
Cohesion or su	9.0-27*

**See Figure 7*

As part of the numerical model setup, soil characterization parameters were incorporated, including shear wave velocities and undrained shear strength. Figure 7 depicts the discretized profiles used in the numerical simulations, based on the measured profiles in-flight. Following preliminary numerical models, the shear wave velocity was adjusted to align with the experimental site frequency, as described in the following section.

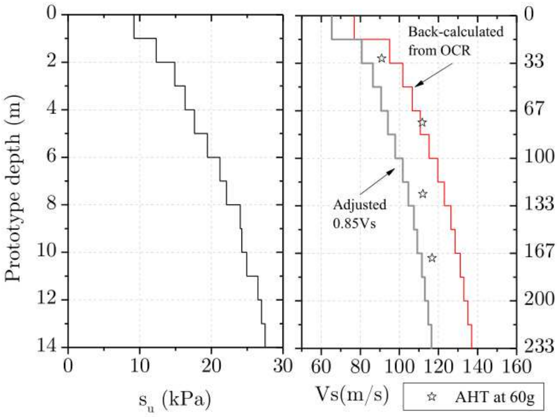

Figure 7. Undrained shear strength and shear wave velocity profiles used in the calculations

5 MODEL VALIDATION

Initially, a comparison was made between the numerical and experimental results in terms of ground surface accelerations, spectral accelerations, and transfer functions. This comparison utilized a low-amplitude input motion with a broad frequency spectrum (EQ2 in Figure 4). Figure 8 shows the results after adjusting the shear wave velocity profile displaying a good agreement between the experimental and numerical data. For the analyses, A1 corresponds to the accelerometer placed at the model surface and A9 represents the data from an accelerometer placed at the base of the model container.

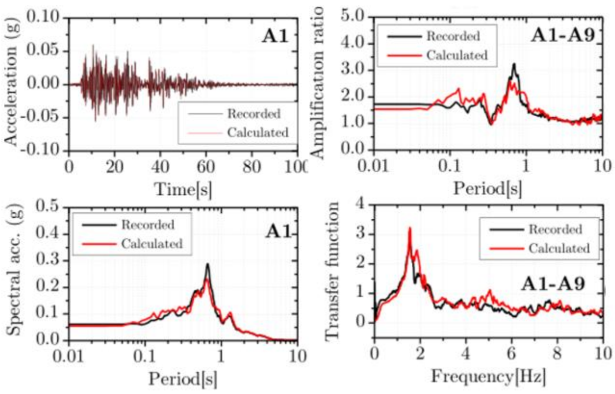

Figure 8. Experimental and measured time-histories at the model surface, spectral accelerations and transfer function.

6 RESULTS

To assess the performance of the numerical simulations, lateral displacements were selected as reference. Horizontal displacements were measured using LVDTs and particle image velocimetry (PIV), enabling the characterization of the displacements during the centrifuge test. For brevity, Figure 8 and Figure 9 present the recorded and calculated responses for one of the earthquake motions depicted in Figure 5. Overall, a good agreement can be observed in the results obtained for earthquake EQ1. Figure 9 demonstrates that both models effectively capture the accumulation of displacements in the downslope direction as the shaking occurs. Two control points (C.P.) were selected for comparing the displacement-time histories at locations corresponding to the depths where the LVDTs were installed.

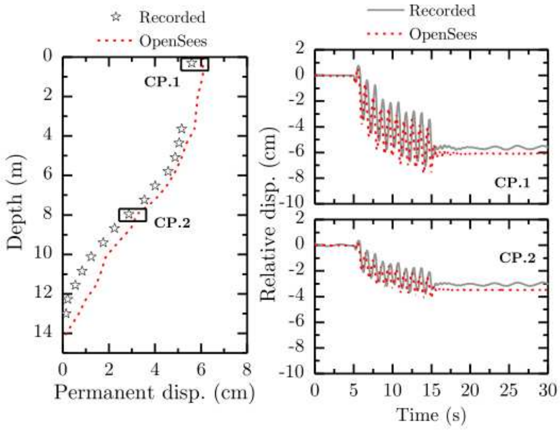

Figure 9. Profiles of permanent displacements and acceleration-time histories at two control points (C.P)

Additionally, from Figure 10 it can be seen that the numerical model captures the acceleration-time histories at various depths preserving its characteristics in terms of the frequency content.

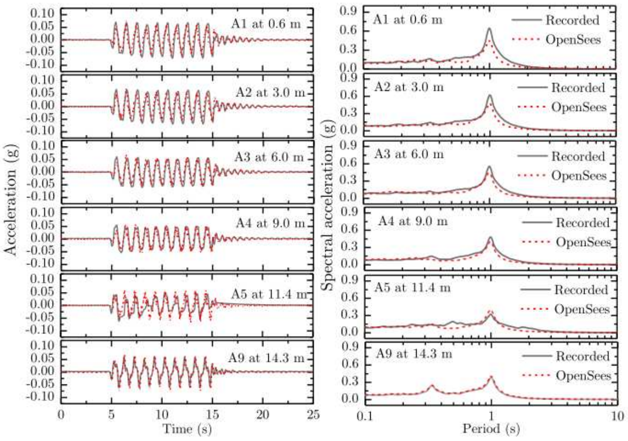

Figure 10. Numerical and measured acceleration-time histories for earthquake EQ1.

7 INFLUENCE OF SLOPE ANGLE ON THE DEVELOPMENT OF SEISMIC PERMANENT DISPLACEMENTS

To further assess the performance of the proposed numerical analysis methodology, additional simulations were conducted. The output of these numerical models was compared in terms of displacement time-histories and permanent displacements at the surface. Figure 11 presents a summary of the displacement-time histories for the input motions applied to validate the numerical model and for various slope inclinations, ranging from a flat condition (zero degrees) to six degrees. The results evidence the influence of ground inclination on the development and accumulation of lateral displacements in the slope, even for relatively small changes in inclination.

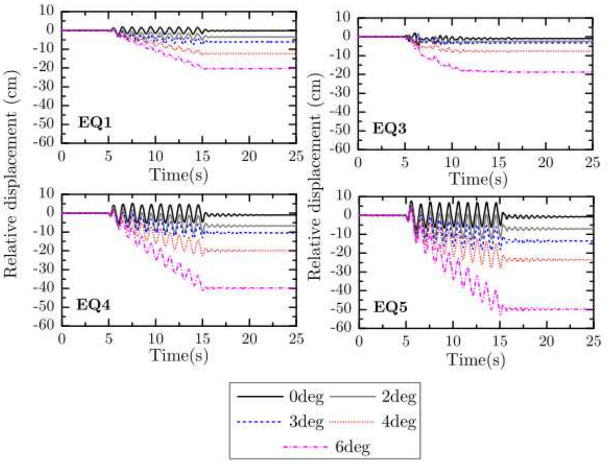

Figure 11. Displacement-time histories for various slope angles

An analysis was conducted to compare the results from the numerical model methodology with the results from an additional centrifuge test consisting on a 6-degrees slope, described by Soriano et al., 2022. The findings demonstrate a good correlation with the measured values from both the three-degree and six-degree experiments (as indicated by the range of measured displacements in Figure 12). This indicates that the adopted numerical modelling approach effectively predicted the response of the six-degree centrifuge test by utilizing the three-degree calibrated numerical model as baseline. The range of permanent displacements from the experimental results underscores the influence of slope angle on models prepared under similar conditions and subjected to identical input motions. For the 3-degree slope model, the maximum permanent displacements recorded were approximately 15 cm, while for the 6-degree slope model, the maximum permanent displacements measured were around 50 cm. The framework of this methodology was applied by Soriano et al., 2024 to simulate the seismic response of gentle slopes in South-eastern Brazil.

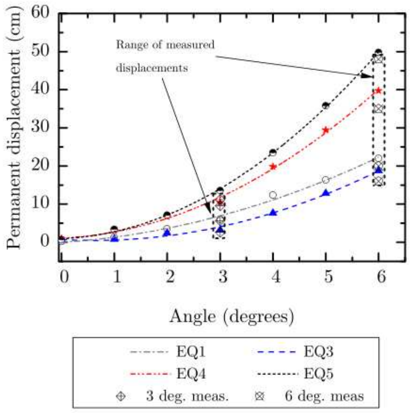

Figure 12. Comparison of permanent displacements at the surface for different slope angles

8 CONCLUSIONS

This paper presented the development and validation of numerical models designed to simulate the experimental response of gentle slopes in soft clay subjected to seismic loading. The main conclusions of the paper are:

- The numerical modelling results were consistent with the experimental results in terms of accelerations and displacements for the applied input motions to the model.
- Simplified parametric analyses were conducted to estimate permanent displacement at the surface of the slope models by means of the proposed numerical modelling approach. The slope inclination

angles in the parametric analyses covered a flat condition and a slope inclination of six degrees for comparison with an additional centrifuge test of the experimental program. The results exhibited good agreement showing the possibility to predict the permanent displacements at the surface of the complementary model. This indicates that the numerical models can be used as a useful tool for the design and evaluation of offshore structures and facilities located on or near gentle slopes in soft clay.

- The seismic response of the gentle slopes exhibits that a slight slope angle increase, can have a remarkable effect on the behaviour of the slopes in terms of displacements for the range of earthquake motions studied. The order of magnitude of permanent displacements of the 3-degree slope model was around 15 cm, for the 6-degree slope model there were measured permanent displacements in the order of 50 cm.

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