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Physical Modelling in Geotechnics

Centrifuge model preparation methodology to simulate a layered gentle slope in soft clay

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ABSTRACT: A dynamic centrifuge test was conducted at the Schofield Centre, University of Cambridge, UK to develop a model preparation methodology to simulate a gentle slope in soft clay, with a strength representative of Brazilian marine subsoils. Speswhite kaolin was utilized for the model preparation as it has comparative datasets with research projects involving physical models. Two types of containers were employed for model preparation. A strongbox for consolidation of the clay and a laminar container to simulate an infinite slope condition. The model was subjected to a series of earthquakes of varying amplitude and frequency content and the response was monitored utilizing accelerometers and displacement transducers. A particle image velocimetry (PIV) setup was proposed to obtain displacements and accelerations from the laminae of the container. This (PIV) method allowed us to obtain additional data that was in good agreement with the measurements from accelerometers and the displacement transducers. The centrifuge test presented in this paper was the first experience in preparing models in clay employing the laminar box at the Schofield Centre. The outcomes of the experiment provide a valuable reference for the preparation of models in soft clay employing a laminar container, and data sets for numerical simulations.

Keywords: seismic response, soft clay, submarine slopes, weak layer, physical modelling.

1 INTRODUCTION

The offshore Campos Basin in Southeastern Brazil is one of the most prolific oil-producing basins in the country. The study of the geological and geotechnical behaviour of the various geomorphological features in this region has been historically motivated by the hydrocarbon industry, and more recently, by the development of renewable energy sources. With these developments, it is relevant the identification of various offshore geohazards: tectonic activity, gravity action, erosion-accumulation effects, coastal dynamic activity, special geologic bodies and human activity (Yincan, 2017).

Among the offshore geohazards, submarine mass movements induced by earthquakes represent a widespread phenomenon around the world, occurring in shallow coastal environments as well as in deep ocean waters (Clare et al., 2018). Many submarine mass movements occur over extended areas with low inclinations, typically 2° to 5° (Piper, 2005). In addition to earthquakes as triggering mechanisms in submarine slopes, the presence of weak layers is a potential in-situ condition for the development of submarine mass movements as they generate a strength contrast between adjacent units of soil (Bryn et al., 2005; Solheim et al., 2005; Locat and Lee, 2009).

This paper presents an experimental methodology developed to simulate the seismic behaviour of a gentle slope in soft clay including a weak layer. The objectives of this work are: (i) to describe the model preparation methodology for simulating a gentle slope in soft clay with an intermediate layer of even softer clay, defined as a weak layer; (ii) to implement a PIV methodology using an open-source code as a complementary source of data in terms of displacements and accelerations at different depth in the slope; (iii) to present the results of the seismic response of the slope and the data generated for further calibrations of numerical and analytical models.

2 EXPERIMENTAL WORK

The physical modelling has become a significant tool to investigate numerous geotechnical problems, characterized by their complex soil and loading conditions. In physical modelling, two approaches can be adopted: (i) full-scale tests (1g); and (ii) centrifuge tests, under higher gravity accelerations (Ng). The dynamic centrifuge tests in this study were conducted in the 10 m diameter beam centrifuge at the Schofield Centre (University of Cambridge). The earthquake motions were applied using a servo-hydraulic actuator developed by Madabhushi et al. (2012). The problem investigated consisted of a semi-infinite sloping ground condition in soft clay. Under these conditions large deformations are expected and therefore a laminar

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container (Brennan et al., 2006) was utilized. The box is 500 mm × 250 mm in length and width and the depth is variable, depending on the number of rectangular frames (laminae) used (280 mm for the current centrifuge test). Further details about this centrifuge experiment are presented by Soriano et al., 2021.

2.1 Materials and Methods

The models were constructed by mixing a slurry of Speswhite kaolin (with a water content of 120%) that was poured into a consolidation container or strong box with the same format and dimensions as the laminar box (250 mm x 500 mm), but higher in depth (500 mm). Speswhite kaolin was selected as it is a widely used material in experimental programs involving physical models. Some properties of the Speswhite kaolin used in the centrifuge test are presented in Table 1 (Lau, 2015).

Table 1. Properties of Speswhite kaolin clay (Lau, 2015)

Property	Value
Plastic Limit (%)	30
Liquid Limit (%)	63
Plasticity Index (%)	33
Specific Gravity, Gs	2.6
Slope of normal consolidation line (λ)	0.22
Slope of unload-reload line (κ)	0.039

2.2 Model Preparation

The centrifuge test performed simulated the seismic response of a gentle slope with a 3-degrees inclination with the presence of a weak layer. Two consolidation pressures of 250 kPa and 125 kPa (for the weak layer) were defined to reproduce an undrained shear strength profile typical of marine clays as the encountered in the seabed of the Campos Basin, Southeastern Brazil (Fagundes et al., 2012).

The following are the model preparation stages to obtain the layered profile for the gentle slope:

1. The kaolin powder was mixed under vacuum with water to obtain a slurry of a 120% water content. The slurry was poured into a consolidation container. A piston was positioned on top of the clay and the consolidation pressures were applied in stages by means of a computer-controlled consolidation rig (Fig. 1). The consolidation lasted twelve days, and it was stopped when settlements were stabilized within 48 hours.

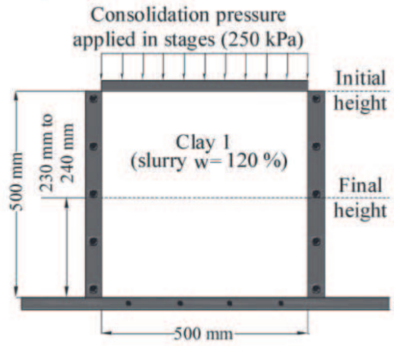

Fig.1. Model preparation: consolidation of the clay.

2. The sides of the consolidation container were removed; the resultant block was split by cutting off the top 80 mm and keeping the remaining 150 mm in the same position. The top block was stored and protected to avoid loss of moisture.

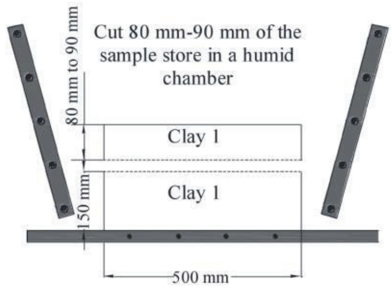

Fig. 2. Model preparation: removal and storage for the top layer of the profile.

3. The sides of the consolidation container were reassembled, and a new layer of the slurry was poured on top of the block of consolidated clay that remained, then, a maximum consolidation pressure of $\sigma'_{v\ max}$ = 125 kPa was applied in stages. At the end of consolidation of the weak layer, the previously stored layer was placed on top of the weak layer and a reconsolidation pressure of 125 kPa was applied to the three-layer clay bed for two days to ensure the continuity between the layers (Fig. 3).

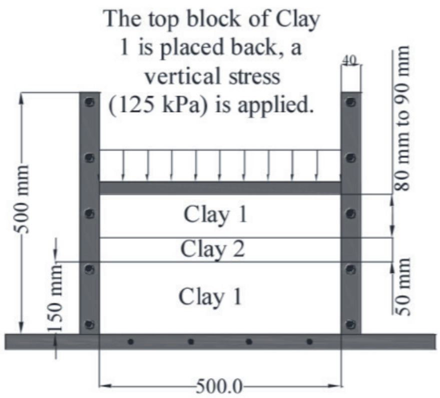

Fig. 3. Model preparation: reconsolidation of the three-layer profile.

4. The applied vertical pressures were removed, and the sides of the consolidation container were again detached. Then the final block of clay was wrapped by a rubber bag to prevent water leakage and to separate the clay and the laminae (Fig. 4). Finally, the frames of the laminar container were assembled around the sample.

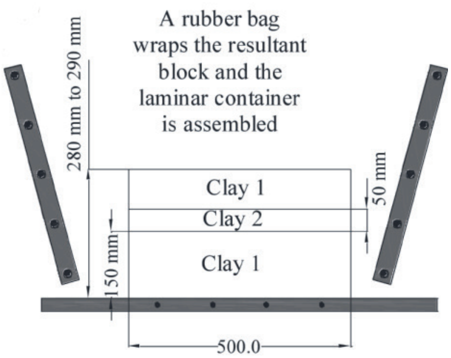

Fig. 4. Preparation of the three-layer profile for installation of the laminar container.

As part of the experimental setup, water content samples were taken at different depths across the clay profile at the end of the centrifuge test. The average water content and degree of saturation of the clay were around 53% and 100% respectively, confirming that during the centrifuge test the clay was in saturated condition.

2.3 Model details

Once assembled the laminar box to the desired height, the instrumentation was installed in the clay profile. The following electronic instruments were used: (i) piezoelectric accelerometers (model A32 by D.J. Birchall Ltd) to record the dynamic motions at different locations in the soil profile; (ii) pore pressure transducers (PPTs, model PDCR-81 manufactured by Druck Ltd.); (iii) Linear Variable Differential Transformers (LVDTs, model DC15 manufactured by Solartron Metrology) to record the horizontal displacements during the swing-up of the model and during the application of the dynamic loads and (iv) a high-speed camera (MotionBLITZ EoSens mini2 produced by Mikrotron GmbH) to track the displacements of a set of markers installed in the laminae throughout the experiment. Fig. 5 presents the location of the instruments and the model geometry and Fig. 6 displays a general view of the model in the centrifuge.

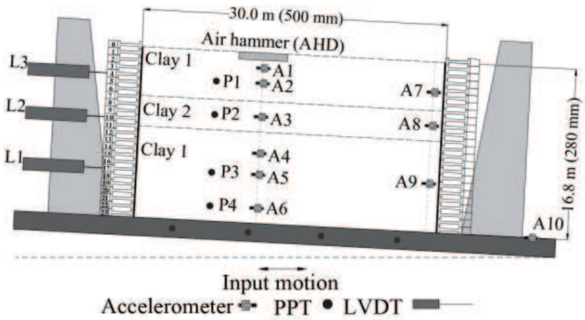

Fig 5. Location of the instruments in the model.

The instruments were installed by excavating small boreholes in the clay and positioning the instruments at the desired depths by means of small probes. The voids were filled with slurry and some of the excavated clay. In addition, a support frame was used to fix an actuator above the model to carry out an in-flight T-bar test. An air hammer (AHD) was positioned on the clay surface to generate shear waves at small strains and calculate shear wave velocities at depths between accelerometers.

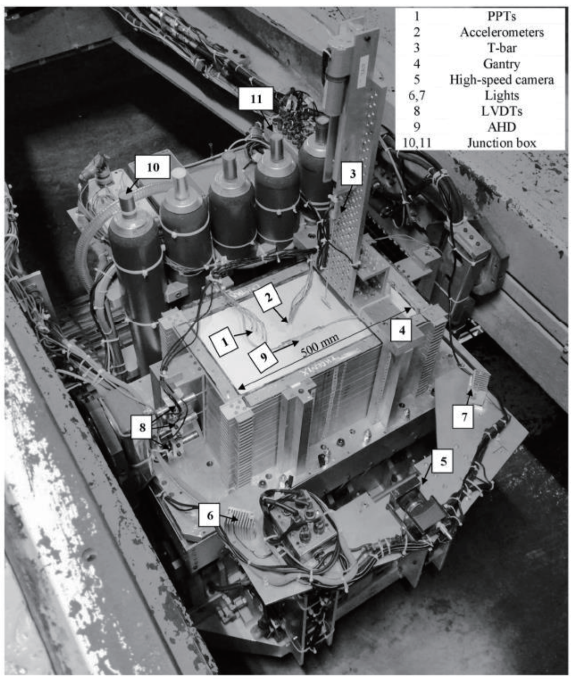

Fig 6. A general view the model.

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2.4 Particle Image Velocimetry (PIV) analysis setup

For the experiment, a high-speed camera developed to record fast processes in confined spaces was employed (MotionBLITZ EoSens mini2 produced by Mikrotron). The resolution of the pictures captured by the camera is linked to the recording frame rate. For example, at a maximum resolution of 1696 by 1710 pixels it is possible to record images at a frame rate of 523 Hz. For the centrifuge test reported here, a resolution of 1504 by 1050 pixels was employed, delivering a frame rate of 953 Hz.

Once the laminar container was assembled and the instruments installed, ArUco markers were glued to each lamina. Two sets of markers were used, the first set, labelled as Fixed column, (Fig. 7) was attached to the vertical, rigid columns that act as a boundary and support for the laminar container in the transverse direction. The displacement of the elements of the fixed column is related to the displacement of the shaking table, enabling tracking of the input motion. The second set of markers, labelled as Displacement markers (Fig. 7), was installed in the laminae of the container and used to track the displacement of the mass of soil at different depths. The three LVDTs installed on the side of the container were also used for comparison with and validation of the displacements tracked by the PIV method.

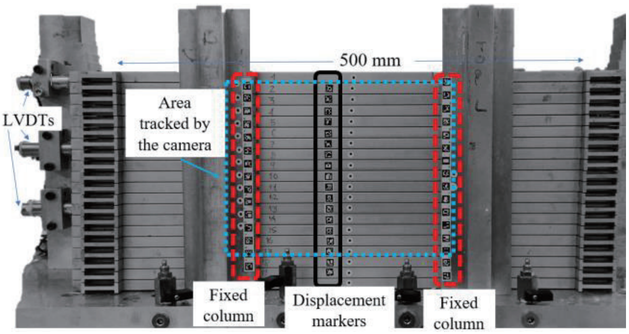

Fig 7. Location and sets of markers for PIV

Blender is an open source software package for many purposes related to 2D and 3D animation (Hess, 2010). Among its functionalities, there is a module for motion tracking that enables tracking of markers during a photo or video sequence. Options such as marker size, tracking area, correlation between matched and source image and tracking methodologies are available. Blender uses a tracker with subpixel precision following a brute-force search with subpixel refinement. For the current test, a correlation coefficient of 0.95 and a tracking method called "Location only", which looks for changes in translation of the markers, was used.

3 EXPERIMENTAL PROGRAM AND TESTING

To simulate the gentle slope inclination, the model was tilted by 3 degrees using wedges placed along the base of the model. The swing up of the model consisted of increments of 10g until reaching the acceleration level for the test (60g). The model was maintained in reconsolidation for 40 minutes before the application of the earthquakes. In the sequence, in-flight characterization tests were carried out to obtain the undrained shear strength profile of the clay and the shear wave velocity at various depths. Fig. 8 shows the measured clay properties and a comparison of the results with the empirical correlations of Wroth (1984) and Viggiani and Atkinson (1995) for the undrained shear strength and shear wave velocity, respectively. Overall, a reasonably good agreement was observed between the experimental and theoretical profiles. From the profiles it can be observed that a strength profile was achieved exhibiting a reduction in the undrained shear strength of around 20% in the weak layer when compared with the neighbouring layers.

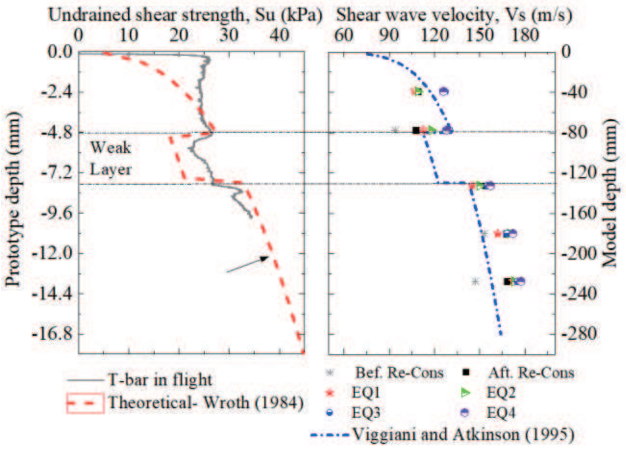

Fig 8. Profiles of undrained shear strength and shear wave velocity

3.1 Shaking events

The model was subjected to four earthquakes, three consisting of sinusoidal motions with a driven frequency of 1Hz and the other, a scaled real motion (Kobe earthquake, 1995). During the application of the earthquakes, the instrument data were recorded at a sampling frequency of 6 kHz. Fig. 9 displays the acceleration-time histories recorded at the base of the model in terms of prototype scale.

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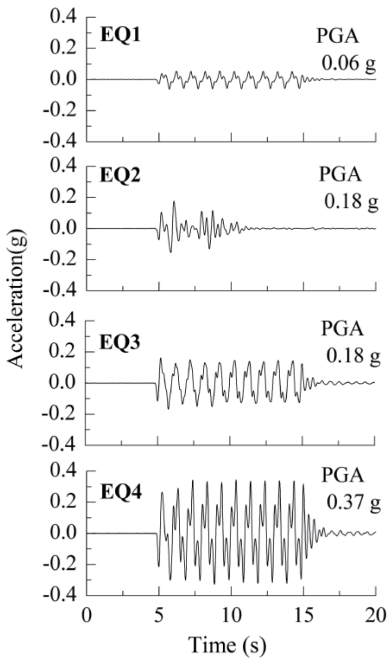

Fig 9. Earthquake input motions applied to the model, measured at the base.

4 TEST RESULTS

As example of the validation of the PIV results, the displacement time histories recorded by the lateral LVDTs and calculated by PIV for one of the earthquakes applied to the model is presented in Fig. 10. The results exhibit an excellent agreement between the data measured by the LVDTs and the calculated from PIV. This validates the use of ArUco markers for tracking the motions of the laminae of the container allowing the measurement of displacements at depths that cannot be measured by the LVDTs due to their size.

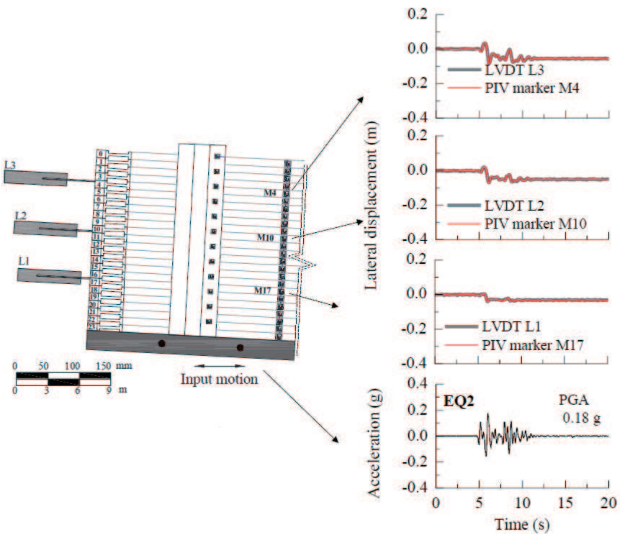

Fig 10. Displacement-time histories measured by the LVDTs and calculated by PIV during earthquake EQ2.

4.1 Peak ground accelerations and lateral displacements

The slope response was evaluated in terms of peak ground accelerations and peak lateral displacements at various depths. The results are summarized in the profiles displayed in Fig. 11. The continuous profile displacements were obtained from the PIV results as they were validated with the measurements of the LVDTs. The PGA profile was built with two sources: the continuous line profile from the PIV using the second derivative of the displacements at each marker depth, and the individual points (labelled as “acc.” in Fig.11) from the accelerometer data. Overall, the displacements display an increase from the bottom to the top as the earthquake amplitude increased with values ranging between 0.08 m and 0.3 m at the top of the slope in terms of prototype scale. The PGA profiles for earthquakes EQ2, EQ3 and EQ4 present an attenuation at the depths between 3 m and 10 m in the soil profile.

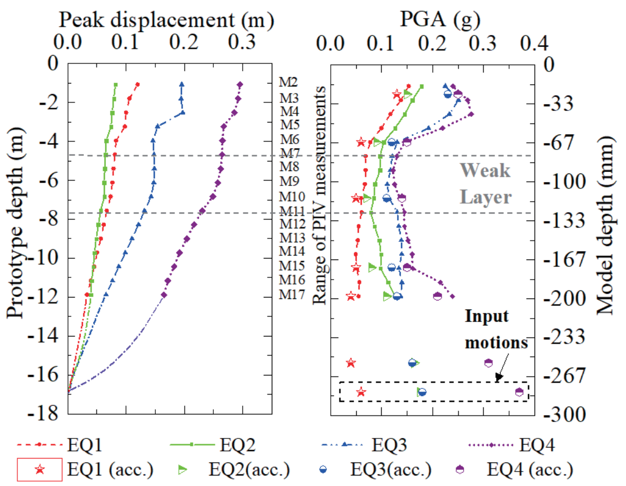

Fig 11. Slope response profiles: peak lateral displacements and peak ground accelerations.

5 POST TEST INVESTIGATIONS

Fig. 12 presents a photograph of the model after the test. An interface line between the clay layers was visible at the periphery of the sample. Thus, to determine the continuity and contact between the layers, a section in the transverse direction was checked. No evidence of discontinuity between the layers was apparent in those transverse sections, therefore, the model soil profile was laterally uniform indicating a successful sample preparation process.

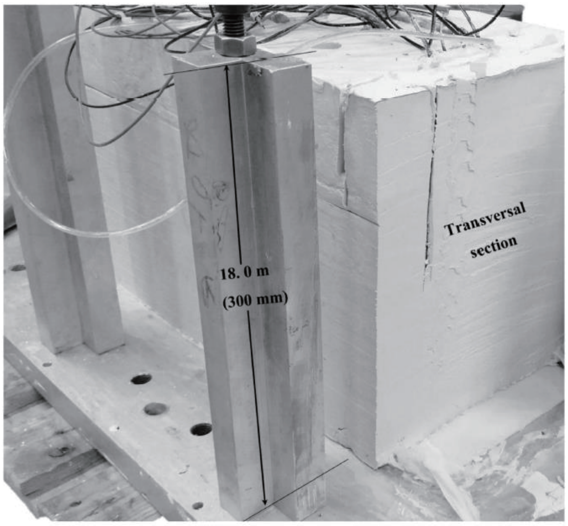

Fig 12. A transverse section of the model to verify the continuity between layer after the centrifuge test.

6 CONCLUSIONS AND RECOMMENDATIONS FOR SIMILAR TESTING PROGRAMS

The centrifuge test in this study was performed to develop a model preparation technique for simulating the dynamic behavior of a gentle layered slope in soft clay. The main outcome from the centrifuge experiment are the following:

- The proposed model preparation technique enabled the simulation of a three-layer soil profile in clay, with a strength contrast between layers of around 20% achieved by applying different consolidation pressures during the sample preparation process.
- The PIV analysis employed to track the displacements of the clay profile at various depths was validated with measurements from the LVDTs. A similar setup can be employed in centrifuge experiments that employ laminar containers.
- The measured soil properties in-flight for undrained shear strength and shear wave velocity were in good agreement with empirical correlations.
- High quality data of accelerations and seismic lateral displacements was obtained from the current centrifuge experiment. The results can be employed for the calibration of numerical models of the problem studied.

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