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Simulation of a Weak Layered Profile Using Geotechnical Centrifuge

Cristian Yair SORIANO[a], Renan Bezerra de ANDRADE[a], Samuel Felipe MOLLEPAZA[a], Márcio de Souza Soares de ALMEIDA[a], Maria Cascão Ferreira de ALMEIDA[b], José Renato Moreira da Silva de OLIVEIRA[a,1] and Pablo Cesar TREJO[a]
[a]*COPPE, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil*
[b]*ESCOLA POLITÉCNICA, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil*

Abstract. Recent site investigations carried out on submarine slopes at Campos Basin offshore of Rio de Janeiro, Brazil detected the presence of weak subsurface layers, which leads to a contrast in resistance of about 30% between the layers. This research aims to replicate the field conditions by creating a clay profile of a weak layer between two strong layers using a geotechnical centrifuge. Speswhite kaolin was used to simulate the marine soil and a mixture of kaolin-bentonite was used as weak layer. Several consolidation and centrifuge tests were carried out in different proportions to simulate the actual field condition. Addition of bentonite to the Speswhite kaolin was found to increase the compressibility and reduce the soil resistance due to its expansive properties. Finally, a three layered profile was selected to simulate the field condition. Both T-bar and cone penetration tests were carried out to measure contrast in the undrained shear strength due to presence of the weak layer.

Keywords. Submarine slopes, weak layers, geotechnical centrifuge, kaolin-bentonite mixture, undrained shear strength.

1. Introduction

Weak layers can play a major role in the development of many submarine landslides. Locat et al.[1] define a weak layer as a layer (or band) consisting of rock or sediment that has strength potentially or actually sufficiently lower than its adjacent units (strength contrast). Shear strength contrast between weak layers and bordering layers of about 50% is not uncommon [2-4].

The understanding of many aspects of submarine landslides, including the location and deduction of weak layers is commonly based on hypothesis, observation and interpretation [5]. The Storegga slide [6], the Nice airport failure [7]and submarine landslides in the fjords [8, 9] are few cases found in the literature that included direct sampling.

Offshore site investigations carried out in anoffshore Brazilian slope detected the presence of a weak subsurface layer. A borehole was drilled in a region composed mainly of submarine canyons in the continental slope located at the north side of the Campos Basin, close to the limits of the estates of Rio de Janeiro and Espírito Santo. Figure 1 shows the undrained shear strength profile and the evidence of strength

[1] Corresponding Author, E-mail: jrmso70@gmail.com

contrast between soil layers. The borehole was executed in a region corresponding to a gentle slope (about 4°). Two types of mud layers were identified at the site. A superficial layer of about 28 m was found over a pre-consolidated older deposits of mud. Figure 1a shows a decrease in the undrained shear strength value (about 30%) between 28 m and 33 m, which proves the existence of a potential weak layer.

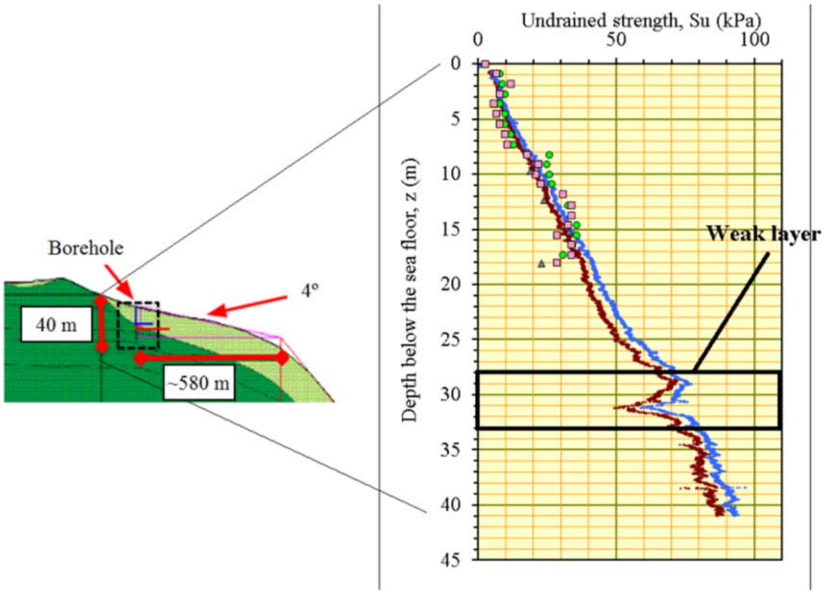

Figure 1. Detail of undrained shear strength profile and evidence of strength contrast between soil layers.

This paper aims to replicate the similar offshore slope at Campos Basin in a geotechnical centrifuge, by creating a clay profile consisting of a weak layer between two stronger layers. Speswhite kaolin was chosen to simulate the marine soil. A mixture of kaolin and bentonite was proposed to simulate the weak layer. The addition of bentonite to the Speswhite kaolin was expected to increase compressibility and reduce soil resistance due to its expansive properties. Four different kaolin-bentonite mixtures were tried in order to determine the mixture that best fits the in-situ condition. Finally, a three layered soil model was tested in the geotechnical beam centrifuge at COPPE/UFRJ to measure the variation of undrained shearstrength with depth by means of T-bar and cone penetration tests.

2. Materials

2.1. Kaolin and Bentonite

The kaolin clay (K) used in the tests is commercially known as Speswhite, which is a highly refined kaolin of ultrafine particle size and high brightness, originated from the southwest of England. This material widely used in research projects involving physical modelling, due to its well documented properties and availability of comparative data sets [10-14].

The bentonite (B) used in the preparation of the mixtures (K+B) with kaolin is an industrial Brazilian sodium montmorillonite commercially known as Brasgel™ [15, 16]. The chemical composition of Brasgel™ bentonite was obtained by performing tests of solubilisation with sulfuric acid. The bentonite is composed of predominantly SiO_2 (silica or silicon dioxide) and Al_2O_3 (aluminum oxide). It also contain iron in the form of Fe_2O_3 (iron III oxide or hematite).

Four different mixtures were prepared according to the following proportions (dry weight basis), as shown in Table 1.

Table 1. Proposed kaolin+bentonite mixtures (dry weight basis).

Mixture	Proportions
M1	95.0 % kaolin (K) + 5.0 % bentonite (B)
M2	92.5 % kaolin (K) + 7.5 % bentonite (B)
M3	90.0 % kaolin (K) + 10.0 % bentonite (B)
M4	90.0 % kaolin (K) + 10.0 % bentonite (B)

Grain size distribution and Atterberg limits tests were performed according to the Brazilian standards. Oedometer tests were performed for virgin kaolin and for the mixtures of kaolin and bentonite. The samples were prepared with a water content equivalent to 1.5 times the Liquid Limit (W_L). Table 2 shows a summary of the geotechnical properties of the materials.

Table 2. Kaolin, bentonite and mixtures soil characterization and oedometer test parameters.

	Sample					
Property	**Kaolin (K)**	**Bentonite (B)**	**M1**	**M2**	**M3**	**M4**
Atterberg limits						
Liquid limit w_L (%)	62	441	65	70	73	84
Plastic limit w_P (%)	23	59	27	31	29	24
Plasticity index PI (%)	39	382	38	39	44	60
Oedometer test						
Water content w (%)	93,0	-	97,5	105,0	109,5	126,0
Initial void ratio e_0	2,43	-	2,54	2,78	2,83	3,37
Compression index Cc	0,44	-	0,51	0,56	0,57	0,73
Compression index $C_C/(1+e_0)$	0,13	-	0,14	0,15	0,15	0,17

2.2. COPPE's Beam Centrifuge

During the first stage of the weak layers research project, centrifuge tests were performed in the mini geotechnical beam centrifuge [17, 18] installed at the Alberto Luiz Coimbra Institute for Graduate Studies and Research in Engineering (COPPE) located in Rio de Janeiro, Brazil.

The mini-beam centrifuge at COPPE has a working radius of 0.66 m and can reach a maximum acceleration of 300 g (9 g-ton at 368 rpm). Figure 2 presents the main dimensions and a photo of the beam centrifuge.

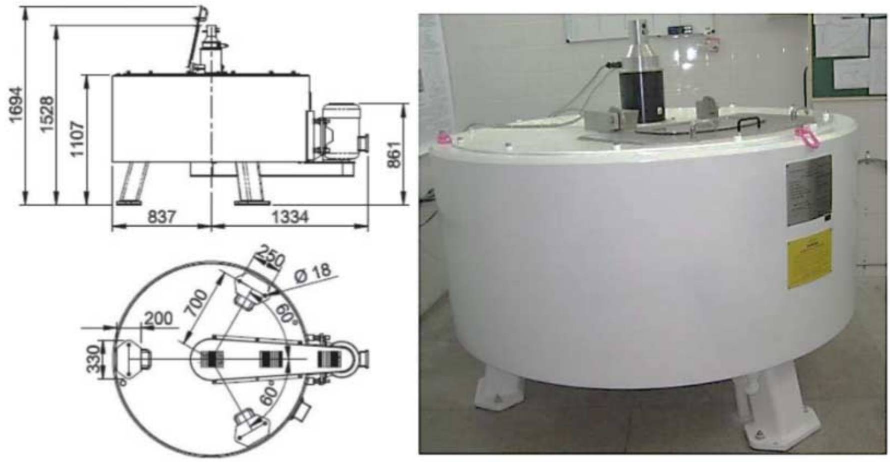

Figure 2. Dimensions and photo of COPPE mini-beam geotechnical centrifuge.

2.3. Centrifuge Equipment

The soil samples used for the centrifuge tests were placed in a 2-D plane strain model container (0.10 m wide, 0.30 m long and 0.18 m high) made from high tensile aluminium.

A mini T-bar penetrometerwas developed to measure continuous shear strength profiles [19]. A mini cone penetrometer having 60° conical tip and 10-mm diameter was also developed for this study. Cone penetration test (CPT) is useful to delineate soil layering, to find the nonhomogeneity within soil layers, and to compare the results with required prototype conditions [20].The dimensions of the T-bar and the mini CPT used in this study are shown in Figures 3a and 3b respectively.

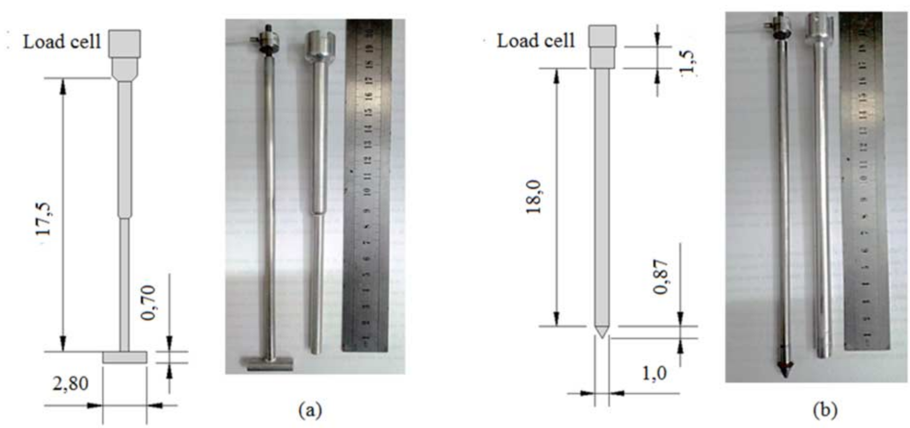

Figure 3. T-bar penetrometer (a) and mini CPT (b) developed for centrifuge tests (dimensions in centimetres).

The undrained shear strength profiles (S_u) are obtained by measuring the vertical force on the load cell installed on top of the T-bar using the Eq.(1) proposed by

Randolph and Housby [21]. The N_b factor recommended by the authors is equal to 10.5 for a bar with average roughness (α=0.5).

$$S_u = \frac{F_v}{N_b D L} \tag{1}$$

where F_v is the measured vertical force, D is the rod diameter (0.7 cm), L is the length of the T-bar (2.8 cm) and N_b=10.5 is the T-bar factor.

3. Methodology

3.1. Model Preparation Technique

The soil sample was composed of three layers. Each layer was placed in the centrifuge container using clay lumps technique. Figure 4 illustrates the clay lumps placed in the model container.

(a) (b)

Figure 4. Centrifuge strong box (a) before and (b) after the clay lumps placing.

A mixture of 90%K and 10%B was chosen to perform the centrifuge tests due to better workability of the mixture. Higher bentonite content (i.e. 15%B) found to produce very soft slurry for the same water content, which collapsed under their own weight. On the other hand, lower percentage of bentonite produced stiffer mixtures reducing their potential effects in simulating the expected strength contrast between the soil layers.

The consolidation of the model was divided into three different stages. First each layer was placed using the clay lumps method, and then they were subjected to a consolidation process as described below. The initial and final height of the model were measured in each step to monitor the settlements during each consolidation phase.

Layer 1: Consists of kaolin with a water content of 1.3 w_L. The initial height of the soil layer before consolidation was 12.2 cm. A steel plate of 1.1 kg was placed on top of the sample to produce a surcharge of 33 kPa to allow the collapse and consolidation of the clay lumps during centrifuge acceleration.The soil sample was subjected to an acceleration of 100 G for 18 hours in the centrifuge.

Layer 2: Composed of a mixture of kaolin and bentonite (90%K+10%B) with a water content of 1.3 w_L. The initial height of the layer before consolidation was 8.4 cm.

The sample was subjected to consolidation under a surcharge of 1.1 kg steel plate at 100G acceleration for 20 hours in the centrifuge.

Layer 3: The top layer was composed of kaolin clay with a water content of 1.3 w_L. The initial height of this layer before consolidation was 9.0 cm. The same method of clay lumps was used to buildthis layer. To achieve the consolidation of the sample, a 1.1 kg steel plate was placed on top of the model and the soil sample was subjected to a 100G acceleration for 24 hours. The second phase of the consolidation was carried out using a 4.2 kg steel plate and subject the soil sample to a 100G acceleration for 24 hours. A total vertical stress of about 138 kPa was applied on top of the sample. An extension piece of the model container made up of acrylic was used to contain the extra height of soil prior to the consolidation.

3.2. Actuation Phase

Model actuation was performed under a centrifuge acceleration of 50G to better simulate the dimensions of the real problem. Two T-bar tests and one Cone Penetration Test were carried out. The positions of the different tests are shown in Figure 5.

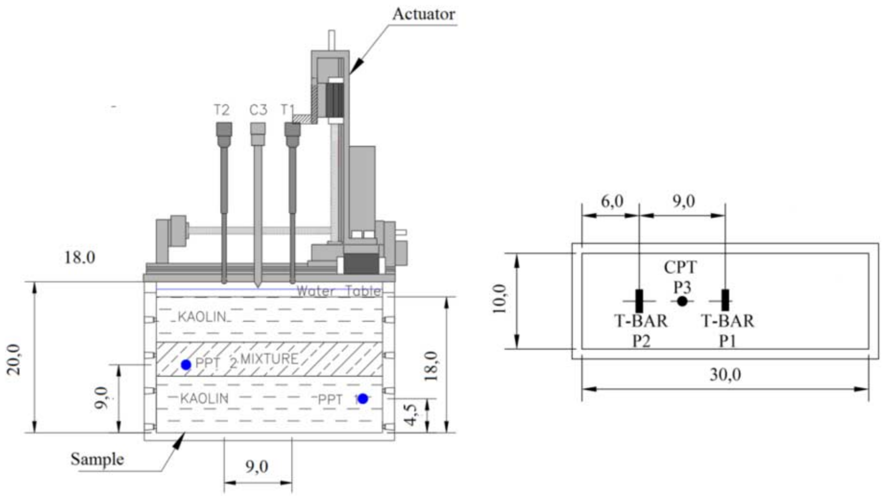

Figure 5. Actuator and location of T-bar and Cone tests.

4. Results and Discussion

Figure 6 presents the undrained shear strength (S_u) profiles of the soil sample. From the figure the location of simulated "weak layer" (mixture of kaolin and bentonite) can be identified. From T-bar test at P1 a drop in undrained shear strength of about 8kPa can be observed between Layer 1 and the weak layer. Shear strength profile from T-bar test at P2 shows a drop of about 4 kPa and a slight variation was observed in case of CPT test. The obtained shear strength contrast was about15% to 30% in case of T-bar tests. This behavior is well compared to the 30% decrease in in-situ S_u value.

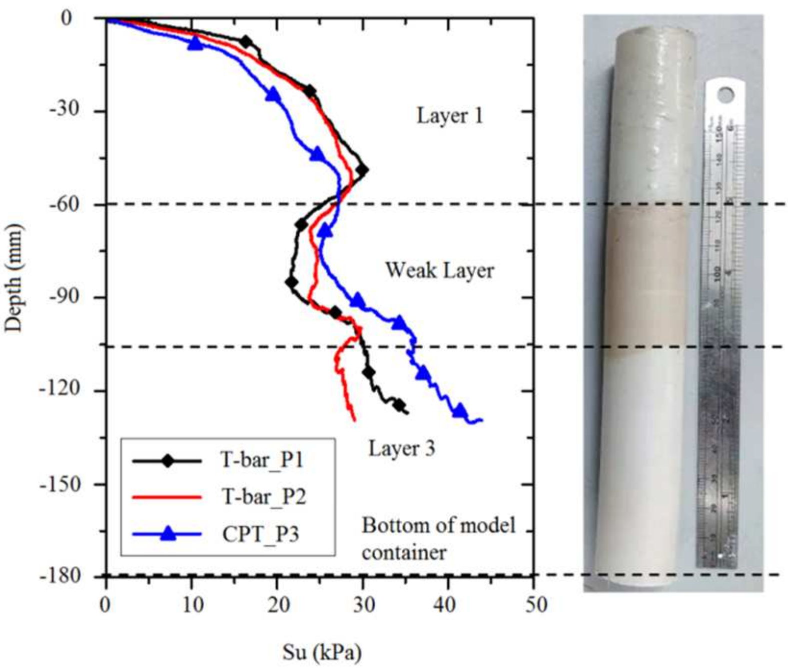

Figure 6. Shear strength profiles using CPT and T-Bar tests.

5. Conclusions

The proposed experimental procedure helps to simulate the contrast in the shear strength profile due to the presence of the weak layer.

The contrast in the shear strength was observed in both T-bar and cone penetration tests.

The reduction in the undrained shear strength due to mixing of bentonite (PI=382%) with kaolin clay (PI=39%) can be explained due to increase in plasticity of the sample (PI=44%). In addition, the bentonite, could have reduced the permeability of the virgin kaolin, leading to a contrast in the degrees of consolidation between the soil layers.

The in-flight consolidation of the model by using the clay lumps technique was found to be time consuming (about 4 days of continuous use of the centrifuge). Alternative 1-g consolidation methods needs to be considered taking into account the procedures, equipment, instrumentation and model container characteristics.

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