Behavior of a submerged reinforced soil slope

Comportement d'un talus en sol renforcé submergé

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ABSTRACT: This paper presents results of the behavior of a submerged reinforced soil by means of centrifuge model tests, numerical analyses and instrumentation. The reinforced soil slope was constructed along the shore of Porto Primavera Dam reservoir, São Paulo State, Brazil. The main purpose of the tests was to verify the deformation of the reinforced mass under construction and flooding. Results from instrumentation installed within the reinforced slope, comprising extensometers and total stress load cells were compared with results from the centrifuge tests and the numerical analyses.

RÉSUMÉ: Cet article présente les résultats d'essais en modèles centrifugés, d'analyses numériques et de l'instrumentation d'un sol renforcé submergé. Un talus en sol renforcé a été construit au long d'une rive du reservoir du barrage de Porto Primavera, dans le État de São Paulo, Brésil. Le principal but des éssais était vérifier la déformation de la masse renforcée, dans les cas de construction et d'inondation. Les résultats de l'instrumentation installée dans le sol renforcé, y compris extensomètres et capteurs de contrainte totale, ont été comparés avec ceux obtenus en essais en centrifugeuses et par analyse numérique.

1 INTRODUCTION

This paper presents a study of a geotextile reinforced soil slope under working load conditions using the centrifuge, numerical analyses and instrumentation. The reinforced slope was built along the shore of Porto Primavera Dam reservoir in the western region of São Paulo State, Brazil. The tests were carried out with the main purpose of verifying displacements within the reinforced mass under construction and after flooding due to filling of the dam reservoir.

2 CENTRIFUGE TESTING

The centrifuge testing was performed using the IPT/Fapesp Centrifuge, the first equipment fully designed, developed and built at the Institute of Technological Research of São Paulo. This equipment was designed in 1990 (Niyama et al., 1994) and with the support of Fapesp-Fund for Support of Research of São Paulo State, was completed in 1995. Figure 1 shows the main components of the IPT/Fapesp double-beam type Centrifuge. It has a rotor of nominal radius 0.75 m and maximum centrifugal acceleration of 200g, with payload capacity of 4.5 g.ton. The image acquisition and processing system is constituted by strobo lamps and a photo camera. As for data acquisition, a slip-ring of 36 channels is available for instrumentation and another 6 channels are available to supply power. Six passages rotation unions were built for hydraulic power supply. The box container is made of steel, with internal dimensions of 30 cm (length), 15 cm (width) and 250 cm (height).

2.1 *Reinforced soil slope model*

Figure 2 shows a cross section of the actual (prototype) reinforced soil slope. The slope face has a 2V:1H inclination, with maximum reinforced height of 7.0m. At the crest of the reinforced mass is placed an embankment with a 2.2H:1V slope protected with gabion mat. The reinforcement used is a polyester nonwoven geotextile (Bidim OP-30) with peak tensile strength of 22kN/m. The reinforcement is 4.80m long and is placed every 30cm in the first 1.50m, after which the spacing increases to 60cm.

The soil used in the reinforced slope is a clayey sand (sandstone residual soil). The reinforced slope mass will be flooded in two stages at the levels shown in Figure 2 due to filling of the reservoir. This flooding was simulated in the centrifuge. A factor reduction of N=50 was used in all tests, employing an acceleration of 50 g.

This study focus on the reinforced slope behavior exclusively under working load conditions, far from failure. Since the interface strength and stress-strain behavior are of secondary importance for these conditions (Abramento & Whittle, 1993), they were not scaled for the model tests.

The only two parameters studied for defining the reinforcement

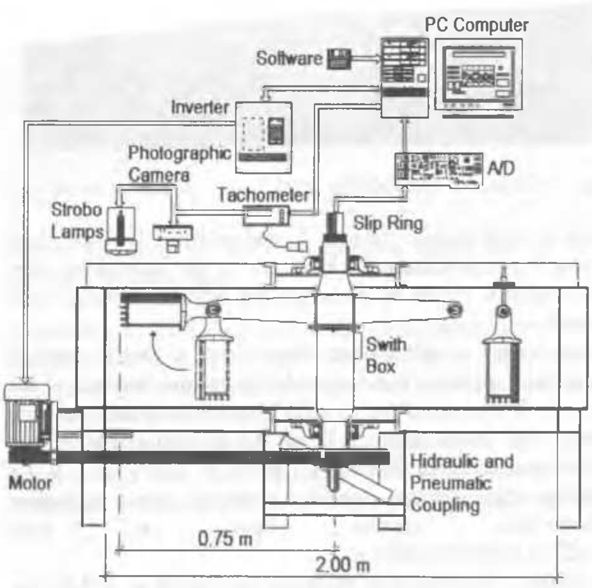

Figure 1. IPT/Fapesp Centrifuge

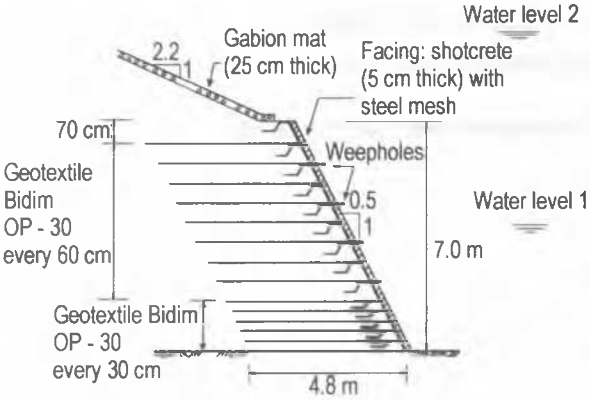

Figure 2. Cross section of reinforced slope

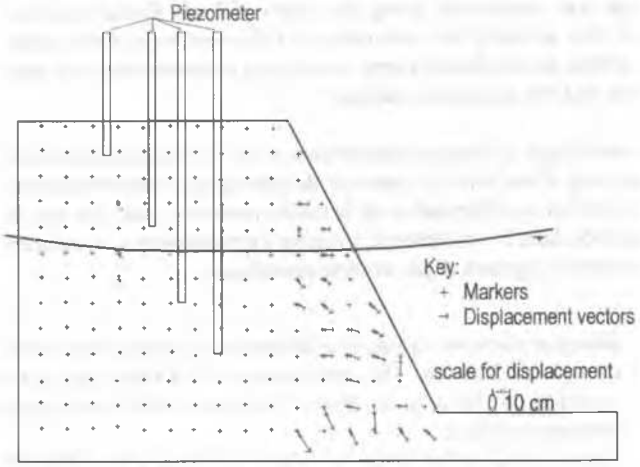

Figure 3. Displacements measured in the centrifuge.

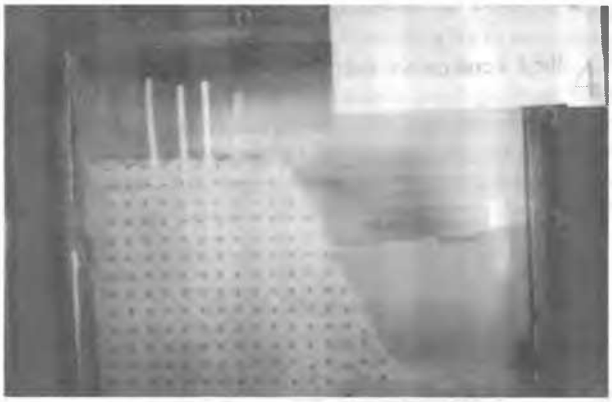

Figure 4. Situation for flooding level 1.

scaling were its tensile strength T_u and modulus J. To select an equivalent reinforcement to be used in the centrifuge tests, load-elongation curves for prototype and centrifuge model were idealized

The equivalent reinforcement should have a tensile strength $T_{u,eq}$ at least equal to the scaled design tensile strength of the geotextile in the prototype (T_d/50) in order to avoid problems related with model failure. Since the geotextile OP-30 has T_u=22kN/m, and considering a factor of safety of 2.0 for obtaining the design tensile strength, the equivalent reinforcement should have at least $T_{u,eq}$=22/(2.0x50)=0.22kN/m.

The catalog reinforcement modulus for OP-30 is J=71kN/m. Therefore, the model reinforcement should have J_{eq}=71/50=1.42kN/m. Several materials, to be used as equivalent reinforcement in the centrifuge were tested in-air in an Instron machine. Test procedures followed the directions given by the Brazilian Code NBR-12824 (ABNT, 1993). Such investigation showed that a perforated plastic sample was within the range of variation of J obtained for the nonwoven geotextile and it was selected to be used for the centrifuge models.

2.2 *Test procedure*

For the centrifuge model, the same soil used in the prototype was employed. Compaction tests showed that the soil had $\gamma_{s,max}$=18.9kN/m^3 and h_{ot}=5.5%. This soil was compacted in the container and samples collected showed that the relative compaction reached 97% and the moisture content ranged from –0.25% to +0.44% around optimum. These results indicate that the soil in the model attained the parameters required at the job site, which asked for relative compaction of 95% and moisture content of ±2% around optimum.

The perforated plastic sheets were placed and wrapped at the front end of the slope, exactly in the same manner it is placed in the field. In order to simulate the surcharge due to the top slope, a weight equivalent to the sloped embankment was placed atop the reinforced slope. Instrumentation was introduced in the model to monitor displacements and water level in the reinforced fill during the tests.

Displacements were followed through special markers glued to the soil, close to glass face, which would follow movements occurring in the soil mass. Four miniature piezometers were installed in different positions in the fill in order to ensure saturation during flooding. The model was then centrifuged to 50g. Flooding was accomplished by running water through a tube running along the hydraulic rotation union at the central axis of the centrifuge. Water discharge was controlled by a specific valve until the desired level was visualized in the container during the experiment. The two levels of flooding presented in Figure 2 were accomplished.

2.3 *Results*

Figures 3 and 4 present typical results obtained in the centrifuge. Figure 3 shows total displacements in the soil mass which occurred since the beginning of the test until after flooding the sample up to the first level as monitored through the special markers. The results show that the magnitude of displacements is relatively small, with maximum “real” (scaled) values of less than 3cm close to the slope face. At the lower region of the soil mass the displacements seem to be larger but were in reality affected by slippage in the markers. The results also show that the displacements are directed towards the wall face, as expected. The piezometers installed within the soil mass showed that saturation was accomplished, as shown in Figures 4 (first flooding level). The magnitude of displacements in the centrifuge are within the range measured by instrumentation installed in the prototype reinforced slope.

3 NUMERICAL ANALYSIS

The centrifuge tests were analyzed using the finite differences program FLAC (Fast Lagrangian Analysis of Continua). FLAC is a bidimensional program based on Lagrangian formulation. The program allows the introduction of cable elements for modeling the reinforcement layers. The construction sequence and two water levels were studied with the numerical analysis. The soil mass was modeled as an elasto-plastic material, with

Table 1: Soil geotechnical parameters

Parameter	Sandstone (Foundation)	Alluvial sand (Fill)
Poisson coefficient, ν	0,39	0,20
Elastic modulus, E (MPa)	280	20
Cohesion, c (kPa)	400	12
Friction angle, ϕ (°)	26	29
Unit weight γ (kN/m^3)	18.0	20.0*

* Determined from compaction tests

Table 2: Reinforcement parameters

Parameter	Geotextile
Rigidity modulus, J (kN/m)	250
Failure load, Tu (kN/m)	22
Thickness (mm)	1.7

Mohr-Coulomb failure criteria. Geotechnical soil parameters for both the fill (alluvial sand) and the foundation soil (sandstone) were determined from conventional triaxial compression tests and are summarized in Table 1.

The load-elongation behavior of the reinforcement used in the wall construction (OP-30) is greatly affected by the confining stress and strain level (e.g. Gomes, 1993). However, the influence of reinforcement stiffness is only important when the ratio Er/Gs (Er=reinforcement elastic modulus and Gs=soil shear modulus) varies more than one order of magnitude (e.g. Abramento & Whittle, 1993). In order to simplify the analysis, a constant value of rigidity modulus J=250kN/m was used in the numerical study. The reinforcement layers were considered fully bonded to the surrounding soil because working load conditions were studied (i.e., far from failure). Other geotextile reinforcement parameters used in the numerical analysis are presented in Table 2.

Figure 5 shows the mesh used in the analysis, which contains 1225 elements. Construction sequence was simulated by eliminating the elements corresponding to the reinforced fill and then activating the soil elements adjacent to each reinforcement layer, from bottom to top, each of them corresponding approximately to each compaction layer 30cm thick. The "wrap around" face, commonly used in geotextile reinforced wall construction, was simulated in the numerical analysis. The lower boundary is considered rigid and rough, fixed in both vertical and horizontal directions. The left boundary is free in the vertical direction. Cable elements were used as reinforcement layers. Three situations were considered for the reinforced fill: dry, and static water at levels 253m and at 259m. Numbers 2 to 11 in Figure 5 represent points along selected reinforcement layers which were monitored during the analysis.

The displacement vectors within the reinforced soil mass for the final construction stage and no water table (Figure 6) shows maximum displacements of around 2cm at the lower portion of the reinforced wall face. Differently from the centrifuge tests, the numerical analysis resulted vertical displacements within all soil mass.

The loads along the reinforcement layers (Figure 7, no water table) reached a maximum value of 1.4kN/m, well below the ultimate tensile strength assumed for the geotextile (22kN/m). This figure shows large force values at the reinforcement tails, demonstrating that the condition of no stress transfer at these points is difficult to simulate in a numerical analysis. In the lower portion shows a superposition of stresses due to the presence of reinforcement at the facing ("wrap around" face).

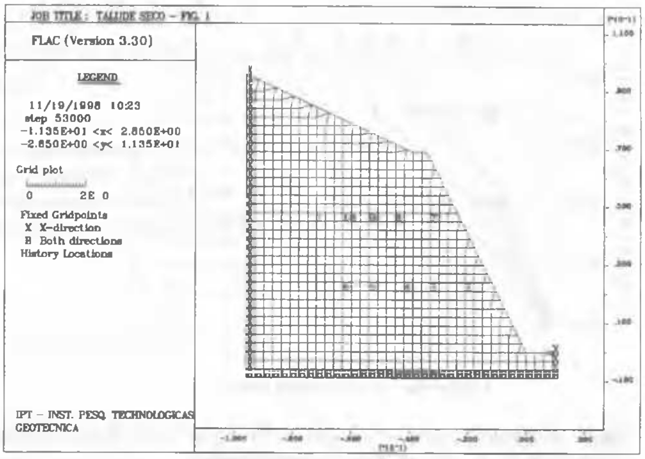

Figure 5. Mesh used in the FLAC numerical simulation.

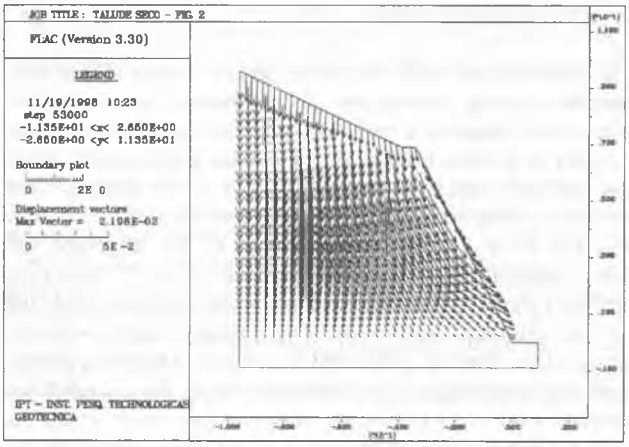

Figure 6: Displacement vectors for the FLAC analysis, no water table.

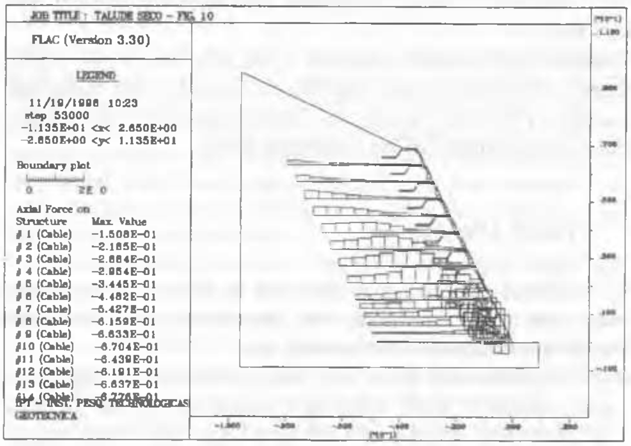

Figure 7: Loads in the reinforcement layers for the FLAC analysis, no water table.

The numerical analysis showed that varying the static water table within the reinforced soil mass had minimal influence on displacements (both in the soil and reinforcement) and loads in the reinforcement layers. However, maximum values of shear stresses at the base of the reinforced wall mass were reached for the condition with no water table.

The plastification diagrams, not shown in this paper, demonstrated that the reinforced soil mass was in elastic conditions throughout the construction and flooding simulation.

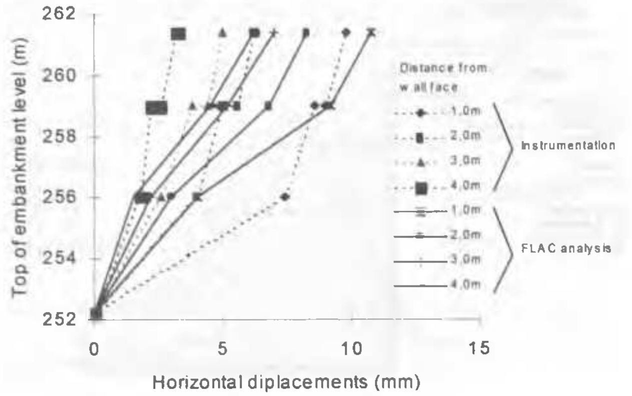

Fig 8 : Horizontal displacements x fill height, level 251,10m, comparing FLAC results and instrumentation

4 INSTRUMENTATION

The reinforced soil wall was instrumented in order to assess its behavior during construction. Extensometers and settlement plates were installed in two sections of the reinforced soil mass in order to monitor horizontal and vertical displacements along the geotextile layers during construction. Two sections were monitored, with extensometers positioned at levels 251.10 m and 253.50 m (lower and upper third of the reinforced soil mass, respectively). Numbers 2 to 11 in Figure 5 (numerical analysis) shows approximate location of extensometers installed in the reinforced soil mass. The instrumentation was not designed to work in submersed conditions. Therefore, results from instrumentation are available exclusively for the condition without water.

Figure 8 shows a comparison of results for displacements at one of the sections during wall construction. Results from numerical analysis agree reasonably well with readings from the extensometers, showing maximum displacements close to the wall face.

Vertical displacements measured in the field (not shown in this paper) were much higher than those obtained in the numerical analysis. This may be due to compaction effects around the plates or settlements of the foundation layer.

5 CONCLUSIONS

A reinforced soil wall was analyzed by means of centrifuge tests, numerical simulation and instrumentation. The main conclusions obtained from the study are:

a) The displacements at the wall face and within the wall mass were relatively small, reaching a maximum of 2cm for both the numerical analysis and the centrifuge test. These results match the displacements obtained from field instrumentation.

b) The stresses along the reinforcement layers determined from the centrifuge tests and from the numerical analysis are very small when compared with the ultimate tensile load of the reinforcement. These results agree with the load levels measured in the field.

c) Both the numerical analysis and the centrifuge modeling showed that saturating the reinforced mass does not imply in significant increase in displacements or stresses in the reinforcements. This observation could not be assessed during flooding of reservoir because the instrumentation was not designed to work submerged.

ACKNOWLEDGMENTS

The authors are greateful to Sofia J.M. Campos for help in running the FLAC analysis, Instituto de Pesquisas Tecnológicas do Estado de São Paulo (IPT), Companhia Energética de São Paulo (CESP), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for their support in the research work.

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