# PHYSICAL MODELING OF REINFORCED EARTH STRUCTURES: GEOTECHNICAL CENTRIFUGES

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## ABSTRACT

This paper presents the principles involved with centrifuge modeling of geosynthetics in earth structures and a case study where geotechnical centrifuge modeling was successfully used. The intent is to illustrate the design of a centrifuge modeling experiment, including proper scaling, selection of g levels, and material selection. The case study involved the feasibility of directly inserting high strength, high permeability geosynthetic composites into marginally stable slopes. This is much like that for wick drains, except the reinforcing elements are inserted in a horizontal direction, rather than vertical. The geosynthetic elements provide soil reinforcement, and also drainage, stabilizing the slope. The simulation of high prototype stresses on the geotechnical centrifuge can be utilized to perform realistic in flight slope reinforcement of large scale earth structures.

*Keywords: Centrifuge, geosythetics, physical modeling, slope, soil reinforcement*

## INTRODUCTION

The use of geotechnical centrifuges to physically model earth structures such as slopes, embankments and levees is well known, and there has been a considerable amount of such studies. A wide range of problems involving Geosynthetics in earth systems are currently being studied using centrifuge modeling techniques. Centrifuge modeling offers the possibility of studying the behavior of model structures under prototype stress conditions and even of simulating critical loading conditions. The use of model test elements usually makes the results of a centrifuge test independent of the laboratory experiments that measure the different parameters involved. This is particularly useful in the case of geosynthetics since the measurement of the physical properties of various geosynthetic materials is sometimes a complex issue. Rather, it is more appropriate to simulate the prototype conditions through proper scaling in a high acceleration centrifuge environment. However when modeling reinforced earth structures attention must be paid to the additional complications that arise from modeling geosynthetics and other similar reinforcing elements.

The paper presents a case study where geotechnical centrifuge models were used to study the feasibility of directly inserting high strength, high permeability geosynthetic composites into marginally stable slopes. The operation is much like that for wick drains as shown in Fig. 1, except the reinforcing elements are inserted in a horizontal direction, rather than vertical. A main advantage of the process is that no excavation is required, making the system attractive economically. A competing process would be the use of permeable soil nails. The geosynthetic elements provide soil reinforcement, and also drainage, stabilizing the slope. Items such as strength, compressibility, and dimensions can be scaled correctly in the model. Common problems when modeling geosynthetics including modeling of geosythethic thickness and installation of geosythethic reinforcing elements at 1g versus high g centrifuge environment are discussed in this paper.

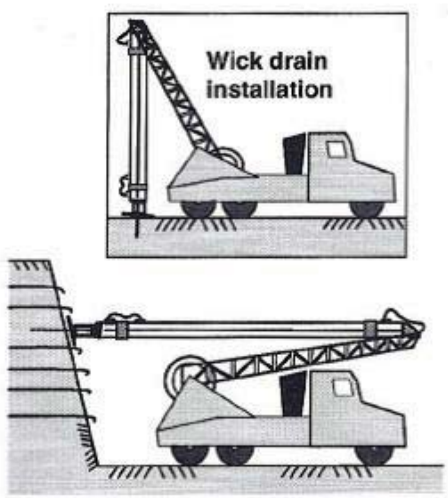


Fig. 1 Schematic of the driving operation (Zimmie et al 2005).

## CENTRIFUGE MODELING CONCEPTS

Centrifuge physical modeling allows simulation of prototype conditions (loading, displacement, flow, failure etc.) under full scale stress conditions through tests performed on small scale models. Thus centrifuge modeling has a distinct advantage over 1g model testing since the properties of any geotechnical medium, such as soil, are highly dependent upon the stress states. For the same reason it is highly desirable to perform tests on earth systems involving geosynthetics at prototype stress states.

The other relevant parameters such as force, displacement, strain, seepage velocity, and etc. are scaled as different powers of the geometric scale of the model (which is also the acceleration level to which the model is subjected). A detailed account of the various scaling laws is beyond the scope of this paper, but the readers are referred to Taylor (1995) and Garnier et al (2007).

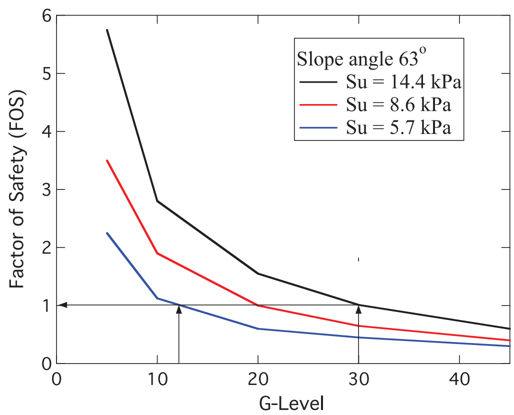


Fig. 2 FOS vs. g-level for various undrained strength for a non-reinforced 63° slope.

The selection of the model parameters and the operational range of *g* levels is based on physical and centrifuge scaling considerations. These considerations provide the practical range of *g*levels at which the prototype will be correctly simulated. In this study, the physical considerations focused mainly on the selection of the optimal slope angle required for a marginally stable slope [factor of safety (FOS) of 1]. This selection is limited by the size of the model container, the properties of the soil samples, and the *g* levels. Limit equilibrium analysis was used to determine the FOS at various *g* levels for different undrained shear strengths of soil. Fig. 2shows a typical relationship between FOS and *g* level for different strengths of soil for a 63-degree slope. A slope of about 63 degrees (1H:2V) was deemed appropriate for the size of model container used. For a range of undrained shear strengths of 5.7 to 14.4kPa, the condition of a marginally stable slope (FOS of 1) can be achieved at *g* levels between 12and 30as shown in Figure 2.

To model soil reinforcement correctly, two similarity requirements have to be satisfied: the axial stiffness and the surface interaction between the soil and the reinforcement (Zimmie and De 1995).The axial stiffness of the geotextile strip will be modeled as where:

$$EA_{(p)} = N^2 EA_{(m)} \tag{1}$$

where $E$ = Young's modulus,$A$ = cross-sectional area of the strip, and $N$ = *g* level.

Subscripts p and m denote prototype and model, respectively.

The second similarity requirement is the surface friction:

$$b \tan_{(p)} = Nb \tan_{(m)} \tag{2}$$

where b and  are the width and interface friction angle, respectively, for the reinforcing strips.

In this study, the reinforcements that were intended to be modeled in the centrifuge tests are high strength composite geotextiles. A non-woven needle punched geotextile was used and has been previously used by various researchers during physical modeling studies (e.g. Guler and Goodings, 1992, Bolton and Sharma, 1994; Porbaha and Goodings, 1996). In this study, the prototype reinforcements being modeled are high-strength composite geotextiles with wide width tensile strengths in the range of 50 to 200 kN/m. Thus it is possible to use readily available geotextiles to obtain the required tensile strength of the model elements.

The various properties of the prototype reinforcement being modeled with respect to the level of acceleration in the centrifuge can be summarized in Figure 3. The ideal *g* level for the tests will be in the range of 15 to 45 *g,* simulating 10- to 30-cm-wide strips. Typical wick drain widths are about 10 cm, with breaking strengths about 135 kN/m (Koerner 1994). Figure 3 can also serve as a design curve for stability computations of full-scale slopes (e.g., to determine the width and the tensile strength of actual reinforcement to be used in full-scale slopes represented by the centrifuge models).

Table 1summarizes the properties of the model reinforcing elements, the simulated prototype elements for a range of 15 to 45 *g,* and the actual available prototype elements. It can be seen that all of the important properties of available prototype material can be modeled closely in the 15-45 *g* range with the exception of thickness. It is difficult to model geotextile reinforcing elements correctly even using the thinnest available geotextile. However, direct scaling of the prototype thickness of the reinforcing element is not very critical as long as the condition for axial stiffness(EA) is satisfied (Zimmie and Mahmud, 1996). Obviously, thethickness has to be in a practical and reasonable range.

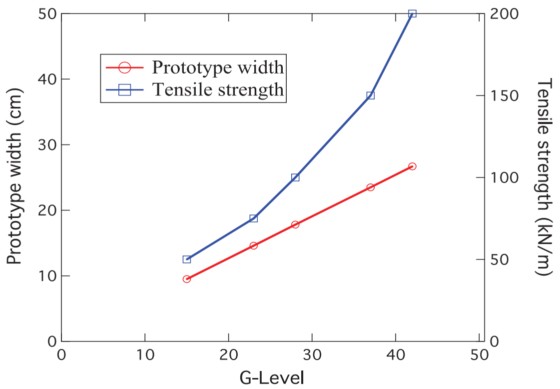


Fig. 3 Properties of prototype strips

Table 1 Properties of reinforcement

| Properties | Prototype | Simulated (15-45g) | Model |
|---|---|---|---|
| Geotextile Type | High strength non-woven | High strength non-woven | Non-woven |
| Thickness (cm) | 0.17-0.25 | 0.7-2 | 0.045 |
| Width (cm) | 10-30 | 10.5-31 | 0.7 |
| Axial Stiffness (EA) (kN) | 42-500 | 56-500 | 0.25 |
| Wide width tensile strength (kN/m) | 50-200 | 72-225 | 5 |
| In plane permeability (cm/s) | 0.4-2.5 | 0.75-2.25 | 0.05 |

## TEST SETUP

The centrifuge tests were performed using the 150 g-ton geotechnical centrifuge at Rensselaer Polytechnic Institute (RPI) in Troy-NY, USA. The experimental setup is shown in Figure 4. The model with a slope of about 63 degrees (1H:2V) was constructed in the strong aluminum box with inside dimensions 610 X 914 X 356 mm, Actuator A moves horizontally, inserting geotextile strips housed inside the mandrels into the soil when the model is at the specified high acceleration level. The mandrels are then withdrawn from the slope, leaving the geotextile strips in place, similar to a wick drain installation. A load cell is used to continuously monitor the driving forces. The strips can be varied on the basis of the location of mandrels placed on the mandrel plate shown by detail A in Fig. 4.

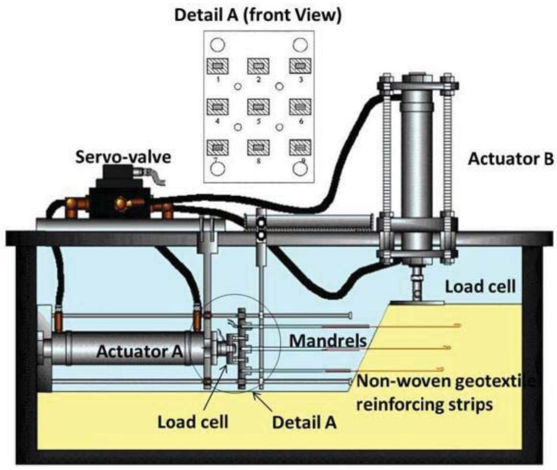


Fig. 4 Experimental setup

The models used kaolin clay, prepared slightly below full saturation and compacted in place in the model in several layers. Laboratory vane shear tests were performed on the samples before and shortly after each centrifuge test. The water contents of the samples were also measured. The relationship between water content and undrained shear strength of the samples of all tests were established.

## TESTING PROGRAM

Four centrifuge tests were performed in this study: (a) model 1 was performed with geotextile strips installed at 1 g; (b) model 2 was performed without any reinforcing inclusions; (c) model 3 was performed with 3 reinforcing strips; and (d) model 4 was performed with 6 reinforcing strips.

For models 3 and 4, the models were spun to the safe or marginal *g* level *(g* level corresponding to an FOS of 1) before the insertion of the geotextile reinforcing strips. Plane strain conditions were simulated by minimizing sidewall friction through the use of Teflonstrips that slid on Teflon sheets glued to the sidewalls of the model container.

Compression load cells were attached to one end of each actuator to monitor the mandrels driving force and the slope crest loading, the load cells are capable of measuring a force up to 900 kg. The deformations of the slope face, toe, and crest were monitored during the experiments by means of linear variable differential transformers (LVDTs) as well as visualization using onboard cameras. Vertical displacements of the grid points located on the slope surface were measured immediately after each test. The data from the LVDTs and the additional measurements made after each test were used to plot the profile of the failed slope.

## TESTING RESULTS AND DISCUSSIONS

The main advantage of using the remotely controlled driving operation in this study is that it allows for reinforcing slopes during in-flight. This is particularly important if the tests are to be more representative of the proposed system, that is, the installation of the reinforcements are achieved under the actual prototype stresses. With this in mind, model 1 was performed with geotextile strips installed at 1 g so that the performance of this reinforced slope could be compared with that of a similar slope without reinforcement. For this purpose, all the nine mandrels (Figure 4) were used to insert the strips into the 63° slope (Su = 8.6 kPa). LVDT measurements of the crest of the slope indicated that this reinforced slope failed at 20 g which is only slightly higher than the marginal g-level of 19 g (which is the g-level corresponding to a factor of safety of one) indicated in Figure 2. The two slopes yielded essentially the same FOS of one, indicating the 1 g installed reinforcement was ineffective. Thus, the reinforcing must be inserted while the centrifuge is spinning.

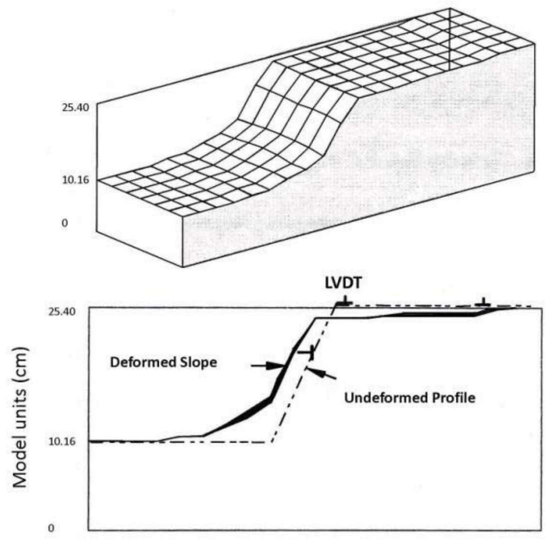


Fig. 5 Slope profiles for unreinforced slope (Model 2).

Model 2 was performed without any reinforcing inclusions and was intended to measure the validity and consistency of the centrifuge experiment. Clay strength of model 2 was 14.4 kPa. During this test, the centrifuge g level was slowly and incrementally increased until the slope failed. The failure was determined by the deformation of the crest of the slope using LVDTs and by visual observation via video recording using onboard cameras. The clay slope with Su = 14.4 kPa failed at about 30g (Fig. 5) which was in close agreement with the limit equilibrium analyses. This indicated the validity of the centrifuge modeling process.

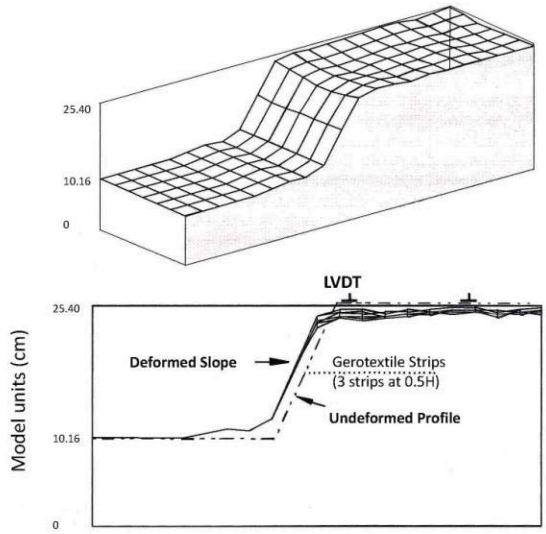


Fig. 6 Slope profiles for reinforced slope by 3 reinforcing strips (Model 3)

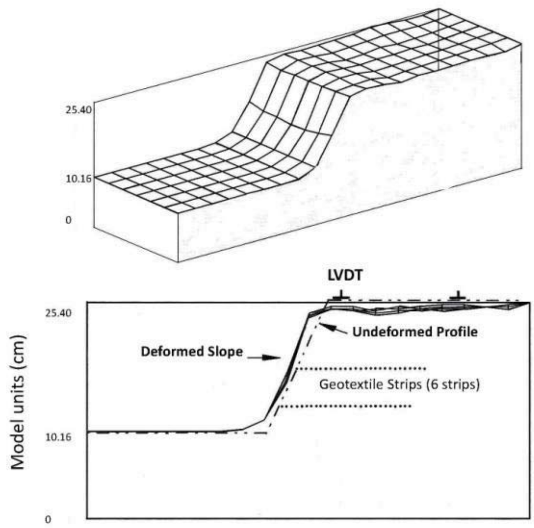


Fig. 7 Slope profiles for reinforced slope by 6 reinforcing strips (Model 4)

Models 3 and 4 were performed to study the effects of the reinforcing inclusions in the slopes. The shear strength of the soil used in these tests was about 14.4 kPa. Strips of reinforcements were installed at 15 g using the remotely controlled hydraulic actuator while the centrifuge was spinning. Three and six reinforcing strips installed in model 3 and 4, respectively. Once the strips were installed into the slope, the centrifugal acceleration was slowly increased to 30 g. At 30 g, the unre-inforced slope having the same soil properties failed (i.e., FOS = 1), as indicated previously in Model 2. Comparing deformed profiles of reinforced slopes from Figs 6 and 7 with unreinforced slope from Fig. 5indicates that the presence of the geotextile strips significantly reduced the deformation. In addition, the deformation was further reduced in the slope by the addition of three more strips (Model 4) as expected.

The side profiles of the slopes in Figs 6 and 7show only minor effects of sidewall friction. A thicker line on the profile of the deformed slope would indicate a large differential settlement between points close to the sidewalls and the points at the center of the slope. As can be seen, there are only minor differences between the center and wall deformations. The use of Teflon strips on Teflon sheets glued on the sidewalls greatly reduced sidewall friction; thus plane strain conditions were essentially achieved.

The driving forces were monitored using a miniature load cell attached into the hydraulic actuator (Fig. 4). A typical plot of driving force versus time required to drive three mandrels in the model slope and minor displacement of the crest vs. time are shown in Fig. 8. The figure indicates that the displacement of the crest of the slope shows only minor heave of the top of the surface during insertion of the mandrel, and minor settlement immediately after retrieval of the mandrels. This indicates that the driving mechanism used in this study causes only minor disturbance to the slope during installation. This observation is critical for designing actual driving mechanisms. Excessive disturbance to the slope during the installation stage, especially in slopes of soft material with marginal factors of safety, could cause failure prior to completion of the installation. It should be also noted that the measured deformation in the crest is rather conservative since all the mandrels were inserted at the same time into the model slope; however, in prototype installations the mandrels will be inserted one strip at a time. Accordingly, the degree of disturbance can be expected to be less than that measured during the tests.

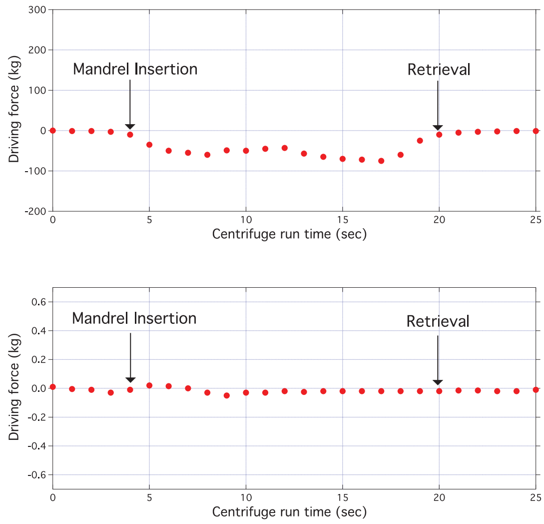


Fig. 8 Measured driving force and crest displacement during insertion and retrieval of three mandrels at 15 g.

## SUMMARY AND CONCLUSIONS

This paper has presented a study where geotech-nical centrifuge physical modeling was used to investigate the feasibility of a new installation methodology for mechanically stabilized earth systems. An in-flight in situ reinforcing method was used to allow high strength non-woven geotextile strips to be driven directly into the face of existing cohesive soil slopes. This method will be particularly viable for stabilizing marginally stable slopes, slopes prone to mud slides, slopes subjected to earthquakes, and marginally stable embankments. In a series of centrifuge model tests, small-scale clayey model slopes were tested at high g-levels to simulate full scale prototype situations of unreinforced and reinforced slopes and installations on site. The test results indicated that the1 g installed reinforcement was ineffective and that the factor of safety was increased and slopes deformed less by the insertion of the reinforcing inclusions. The tests appear to justify the feasibility of the proposed method of slope reinforcement as a rapid and economical retrofit technique. Moreover, the feasibility and cost effectiveness of the proposed methodology can only be truly verified after full scale installations are completed. In addition to presenting the research results, the intent was to present the typical design details of a centrifuge experiment.

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