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Instrumentation for centrifuge modeling of geotextile reinforced slopes

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ABSTRACT: The geotechnical centrifuge at Rensselaer was utilized to study the feasibility of installing high strength geotextile strips in soft soil slopes, to perform as reinforcing elements and drainage media. Small strips of nonwoven geotextile, less than six mm wide, were driven into marginally stable slopes while the centrifuge was in flight. A "mini-robotic" system was used to install the reinforcing strips which were instrumented with miniature strain gages. Various instrumentation was used to monitor the slope deformation, driving forces, crest loading and pore water pressure.

1 INTRODUCTION

Research on the application of geotextile strips as reinforcing elements in marginally stable soft soil slopes was performed using the geotechnical centrifuge at Rensselaer. A series of geotechnical centrifuge model tests were utilized to study the feasibility of installing high strength geotextile strips in soft soil slopes, to perform as reinforcing elements and drainage media. The geotextile strips were inserted horizontally, directly into the existing slopes at corresponding prototype stresses. Instrumentation was one of the challenging aspects of the modeling work. When working with the centrifuge models, the elements being modeled must be scaled down by the level of the centrifugal acceleration, i.e. the g-level employed in the modeling process. This results in the use of miniature reinforcing elements, i.e. very small geotextile strips which are difficult to instrument. In this study the small strips of nonwoven geotextile, less than six mm wide, were driven into the marginally stable slopes while the centrifuge was in flight. These strips were instrumented with miniature foil type resistance strain gages. The various stages of mounting and installing the strain gages on non-woven geotextile strips, including the required curing of the bonding agent and the use of thin coatings to protect the gages from damage during the model tests, are presented herein.

To properly simulate full scale installation of the strips into the slopes, the reinforcing strips must be driven while spinning the centrifuge at the desired g-level. A remotely controlled miniature mandrel driver wass used, and the driving forces were monitored using compression load cells. Results from some of the tests are presented herein.

2 CENTRIFUGE MODELING

Centrifuge model experiments related to slope stability and seepage in slopes have been performed by many researchers. Schofield (1978), Kim and Ko (1982) and Gorrill and Mitchell (1988) have reported centrifuge experiments to study the failure of slopes under various loading conditions. Malone et al (1988) have performed experiments studying seepage through slopes and Kenney et al (1977), Resnick (1988) and Resnick and Znidarcic (1990) have studied the effect of installing horizontal drains in slopes to minimize seepage and improve slope stability. Most of the model experiments reported in the literature were performed on saturated fine grained soils. Kim and Ko (1982) and Gorrill and Mitchell (1988) performed centrifuge tests at different g-levels and thus modeled the stability of prototype slopes of different heights. The study by Gorrill and Mitchell (1988) included different configurations of crest loadings on the tops of slopes using four different angles of inclination. Kenney et al (1977) conducted 1-g laboratory scale model tests using two different slope conditions in which the phreatic surface in the slope was monitored by means of piezometers. The effect of horizontal drains was studied by monitoring the piezometric surfaces with different configurations of drains in the slopes. From this study Kenney et al (1977) produced charts that may be used in the design of horizontal drains in slopes. The validity of such design charts in full-scale situations was studied by Kim and Ko (1982) utilizing centrifuge experiments at the University of Colorado. The use of high acceleration fields in geotechnical centrifuges in all the above cases and in the work presented herein simulated stress conditions and seepage forces similar to full scale prototype slopes.

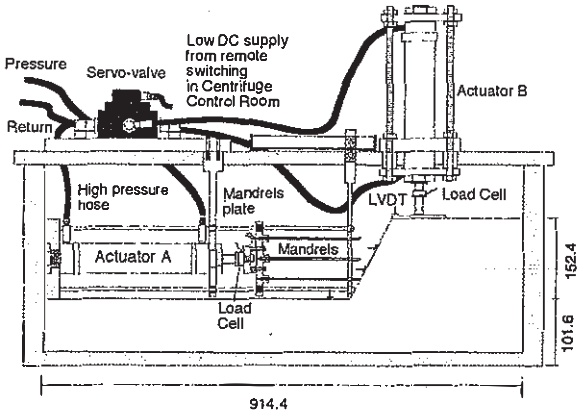


Figure 1. Experimental setup

Instrumenting geosynthetic material, especially geotextiles, may not be trivial. The irregularity and inconsistency in the surface texture makes them a poor bondable material. The use of conventional adhesives proofed generally is inadequate. Work performed by Sluimer and Risseeuw (1982), and Leshchinsky and Fowler (1990) shows that the use of silicone adhesive such as Terostat 33, provides the required bonding between the strain gage and the surface of the geotextile specimen. An appropriate clamping force was also required to impregnate the adhesive into the void between the geotextile yarns.

2.1 *Centrifuge experiments*

Centrifuge experiments were performed on the 100 g-ton geotechnical centrifuge at Rensselaer Polytechnic Institute. The models utilized kaolin clay, prepared slightly below full saturation and compacted in place in the model in several layers. From considerations of similitude, preliminary calculations indicated that proper scaling could be achieved in experiments conducted between 20 and 100 g's. A slope of about 1H:2V (63^o) was used in the tests. This slope angle used for the model slope was deemed appropriate for the size of model box used. At this slope angle, the model could be tested up to 35-g, thus modeling the required properties of the actual reinforcing elements in the prototype slopes. The model was spun to this safe or marginal g-level (g-level corresponding to a factor of safety (FOS) of one) prior to the insertion of the geotextile reinforcing strips. Plane strain conditions were simulated by minimizing side wall friction, through the use of Teflon strips which slid on Teflon sheets glued to the side walls of the model container.

A strong aluminum box with inside dimensions 610 mm x 914 mm x 356 mm was used for the tests. The experimental setup is shown in Figure 1. Actuator (A) moves horizontally, inserting geotextile strips housed inside the mandrels into the soil. This operation occurs while the centrifuge is in motion and the model is at the specified high acceleration level in order to simulate prototype soil stresses in the slope. The movement of the actuator is controlled remotely from the centrifuge control room by means of hydraulic servo-valve systems. The mandrels are then withdrawn from the slope leaving the geotextile strips in place, similar to a wick drain installation.

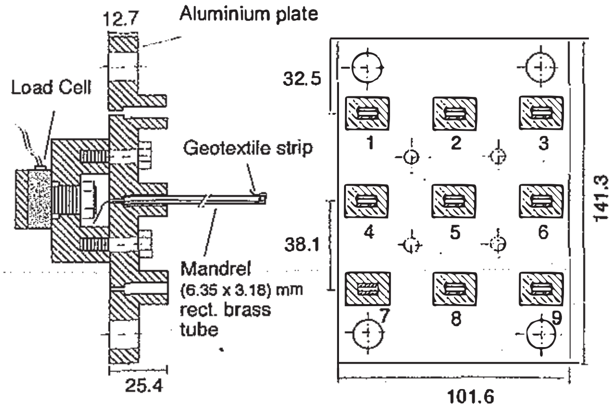


Figure 2. Mandrel head assembly

The geotextile strips were installed in the slope using a mandrel head assembly shown in Figure 2. An aluminum plate was attached to the end of the actuator (A). The plate was fabricated to enable the attachment of up to nine mandrels to the plate, configured as shown in Figure 2. The positions of the mandrels are numbered one through nine and these also indicate the various configurations which the geotextile strip arrangements in the slope can take. Actuator (B) is used to apply a gradually increasing surcharge loading on the slope after the strip installation process is complete. A load cell is used to continuously monitor the load.

2.2 *Instrumentation*

Various instrumentation was used in the model. Washer type compression load cells were attached to one end of the actuator rod. The load cells are capable of measuring a force up to 900 kg. The load cell attached to actuator (A) was used to monitor the mandrels driving force, and the load cell on actuator (B) monitored the crest loading.

The deformation of the slope face, toe and crest were monitored during the experiments by means of LVDT's (Linear Variable Differential Transformers) whose positions are shown in Figure 1. The vertical displacements of the grid points printed on the slope surface were measured immediately after each test. The data from the LVDT's and the additional measurements after each test were used to plot the profile of the failed slope.

3 STRAIN MEASUREMENT

By definition,

$$k = \frac{\Delta R/R}{\Delta L/L}$$

$$\frac{\Delta R}{R}=k\frac{\Delta L}{L}=k\varepsilon \qquad (1)$$

where k is the strain sensitivity factor and most often a manufacturer's gage factor (Gf) is used instead. Gf is generally slightly lower than the strain sensitivity factor due to the variation in the grid design of the strain gage. $\Delta R/R$ and $\Delta L/L$ (ε) are the unit change in resistance and length of the gage respectively.

The schematic of the strain measurement system is shown in Figure 3. R_{AC} and R_{BD} are the active gages and R_{AD} and R_{CB} are the identical dummy gages. Under a balanced bridge condition (no straining);

$$R_{CB}=R_{BD}=R_{AD}=R_{AC}=R$$

$$V_A=V_B=\frac{R_{AC}}{R_{AC}+R_{AD}}V=\tfrac{1}{2}V \qquad V_o=0$$

where V_A and V_B are the output voltage at point A and B respectively and V_o is the voltage across AB and V is the bridge excitation voltage.

When the gage is strained by ε ($\Delta L/L$), R increases by ΔR

$$R_{AC}=R_{DB}=R+\Delta R \qquad \textit{(for active gages)}$$

$$R_{AD}=R_{CB}=R \qquad \textit{(for dummy gages)}$$

The output voltage, V_o, is equal to V_A - V_B

$$V_A=\frac{R_{AC}}{R_{AC}+R_{AD}}V=\frac{R+\Delta R}{2R+\Delta R}V$$

$$V_B=\frac{R_{CB}}{R_{CB}+R_{BD}}V=\frac{R}{2R+\Delta R}V$$

$$V_o=\left(\frac{R+\Delta R}{2R+\Delta R}-\frac{R}{2R+\Delta R}\right)V \qquad (2)$$

Substituting Equation 1 into Equation 2,

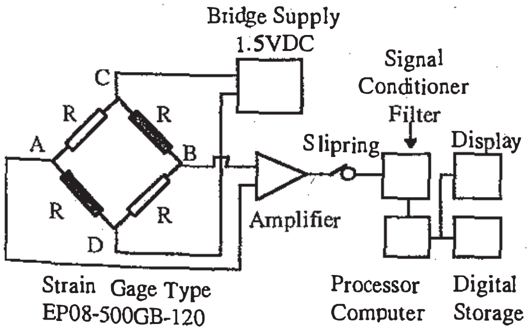


Figure 3. Strain measurement system

$$V_o=\left(\frac{1+ke}{2+ke}-\frac{1}{2+ke}\right)V$$

$$\frac{V_o}{V}=\frac{k\varepsilon}{2+k\varepsilon} \quad \text{or} \quad \varepsilon=\frac{2V_o}{k(V-V_o)} \qquad (3)$$

Equation 3 was used to compute the strain. The output signals received from the strain gages were transmitted through the centrifuge sliprings.

Each geotextile reinforcing strip was instrumented with a set of two strain gages. Two additional strain gages were mounted on a rigid block, as dummy gages, to complete the bridge circuit. Strain gage types EP-08-500GB-120, manufactured by the Micro Measurement Group were used. This type of strain gage is capable of measuring large strains. Typical ranges are ±10% for gage lengths less than 3.2 mm and ±20% for gage lengths greater than 3.2 mm. These strain gages are commonly used for measuring large strains in nonhomogeneous materials where the average strain is of most importance. The attachment technique was performed in a similar manner as presented by Sluimer and Risseeuw (1982). They applied a thin layer of silicone glue to the geotextile. Next, as much glue was scraped off the surface as was possible. The strain gage was then pressed into the glue and covered by a thin Teflon strip, clamped and cured. The attachment was further enhanced by incorporating the technique recommended by Wu (1992). Wu suggested that only the two extreme ends of the high elongation strain gages should be glued with epoxy, to eliminate the influence of the deformation characteristics of the adhesive on strain measurements.

Thus, glue was applied beneath the gages as well as at the ends. In brief, the gage mounting technique employed is as follows: silicone adhesive was used to mount the strain gages to the geotextile strip while epoxy glue was applied at the two extremities of the gage. An appropriate clamping force was applied with proper padding to protect the gages, thus allowing the silicone adhesive to impregnate through the fibers of the geotextile. This provides a homogenous bonding of the gages to the strip and a more rigid bond at the extreme ends. This method proved to be more favorable than the method used by Sluimer and Risseeuw (1982) and provided better accuracy. The comparison between the two methods will be discussed later. A protective coating of a solvent-thinned silicone rubber was then used to protect the gages after installation. The coating cures to a tough rubbery transparent film of minimal thickness (film thickness per coat is about 0.4-0.5 mm). This type of coating is suitable for applications which require a high degree of protection and minimal coating thickness.

4 CALIBRATION

A series of tests were performed to calibrate the strain gages. Calibration tests were performed to

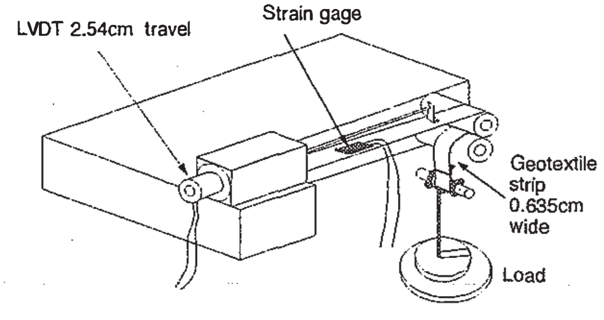


Figure 4. Calibration setup

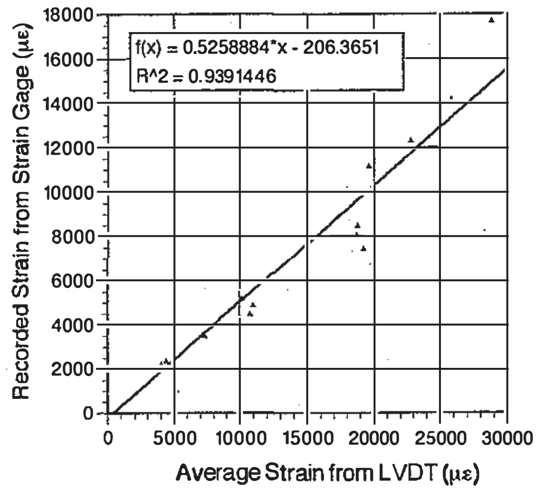


Figure 5. A calibration plot

check the responses of the strain gages with respect to the different methods of gage mounting. The recorded strain from the strain gages at various stages of loading were compared with the average strain from the LVDT mounted on the same strip.

The setup for the calibration test is shown in Figure 4, and Figure 5 shows a typical calibration plot. As shown in Figure 5 the strains recorded by the strain gages are about 52% of the average strains measured by the calibration LVDT. Even though the strain measured by the strain gages attached on the strips does not agree with the average strain measured by the LVDT, the relationship between these measurements is quite consistent and the mounting technique is highly reproducible. The 52% strain value agrees well with other strain instrumented geotextile projects (Sluimer and Risseeuw, 1982 and Wu, 1992). The effect of various strain mounting techniques on the strain gage measurement is summarized in Figure 6. Gage 1 and Gage 2 were mounted using the method specified above and Gage 3 was mounted using silicone adhesive only (Sluimer and Risseeuw (1982) method)., Both Gage 1 and Gage 2 indicate about 52% of the average strain from the LVDT. The strains from Gage 3 are measuring only about 30% of the average strain.

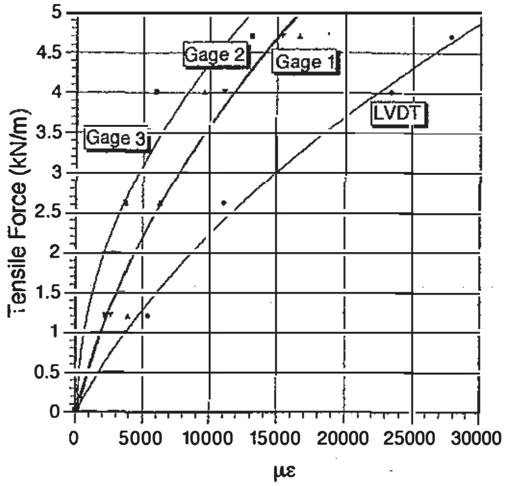


Figure 6 Tensile-strain (different gage attachment methods)

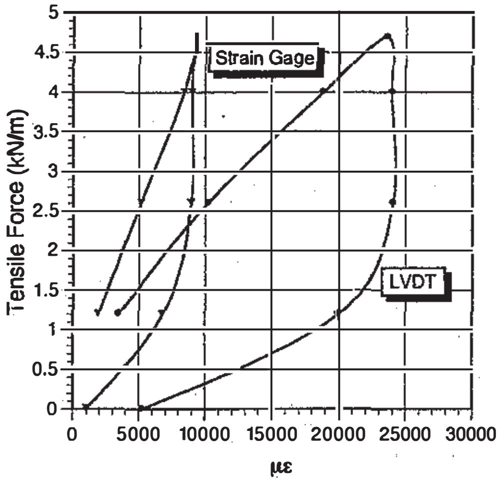


Figure 7. Tensile-strain plots (AE15)

The use of the adhesive (AE15) recommended by the manufacturer, which allows strain measurements up to 15% was tested and compared with the method used in this research. Figure 7 show a loading cycle with strain measured by a strain gage mounted using AE15 compared to the average strain from LVDT measurements. The strain gage is measuring about 40% of the average strain. The measurement using the mounting technique used in this study is shown in Figure 8, and the measured strains are about 55% of the average strain.

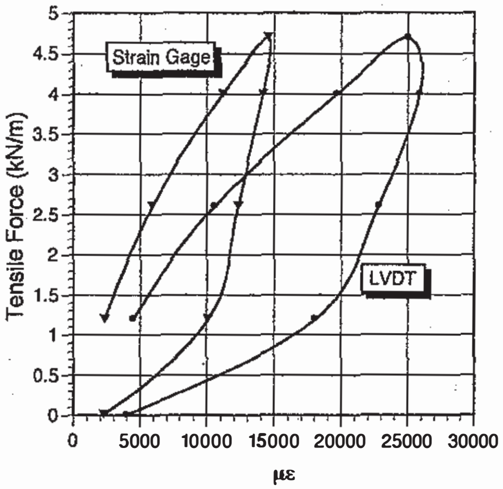
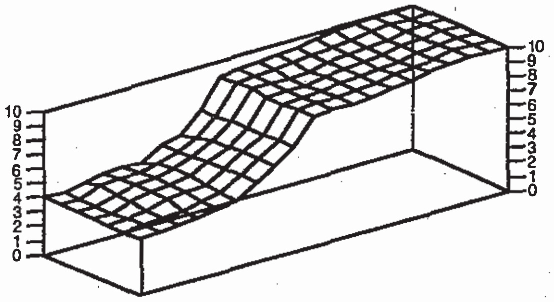


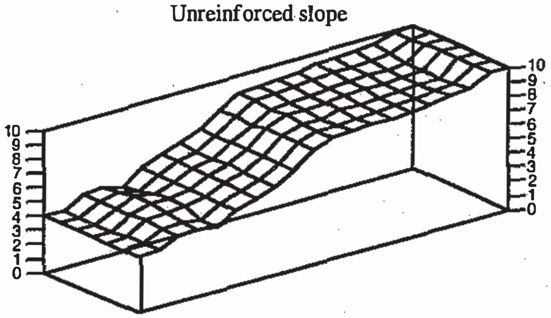
Figure 8. Tensile-strain plots (silicone/epoxy)

5 RESULTS

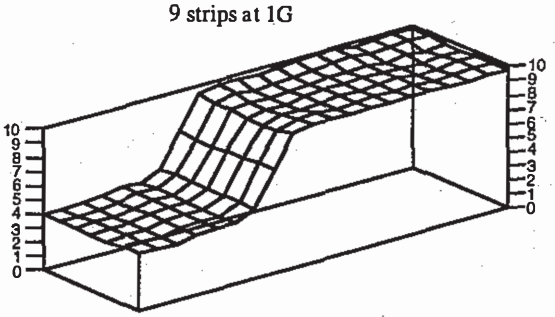
The displacements of the slope surface, crest and toe provided by the LVDTs, and additional measurements after each test were used to plot the failure profile for each slope. The results from some typical tests are shown in Figure 9. The failure profile for the unreinforced slope showed a classical circular arc failure, and a tension crack was visually observed at about 10 cm beyond the top edge of the slope. The clay in this slope had an undrained shear strength (S_u) of 5.72 kPa, and failed at about 12g. The maximum g-level for a marginal factor of safety (FOS ≈ 1) for this slope was about 12-g for the 63° slope. In another test, nine geotextile strips were installed manually at 1-g. All the nine mandrels (1 through 9) were used to insert the geotextile strips into the 63° slope. After all the nine strips were installed, the model was tested in the centrifuge. The centrifuge was spun up to 5-g and stayed at that g-level for 5 minutes. The g-level was increased gradually with increments of 5-g until the slope showed substantial failure. Failure was determined by the LVDT's measurement of the crest of the slope, and by visual observation of the generation of tension cracks, using the closed circuit TV in the centrifuge control room. For this test the slope failed at 20-g which is only slightly higher than the marginal g-level (the g-level corresponding to a factor of safety of one). Using Taylor's stability chart to compute the factor of safety for this slope with clay having an S_u of 8.46 kPa, the marginal g-level is about 19-g. Thus, there was no significant increase in the factor of safety when the reinforcing strips were installed at 1-g. In one of the tests where the geotextile strips were installed in flight, three strips were installed at 15-g into a clay slope with an undrained shear strength of 14.4 kPa. The model was spun up to 15-g prior to the insertion of the reinforcing strips. Three mandrels (positioned at 4, 5 and 6 as shown in Figure 2) driven by a remotely controlled actuator were used to insert the strips into the slope. The slope profile plotted from the measurements of the displacement of the surface of the slope did not indicate any substantial deformation at the marginal g-level (30-g), as can be seen in Figure 9.



Unreinforced slope



9 strips at 1G



3 strips at 15G

Figure 9. The slope profile for various tests (vertical dimensions in inches)

To properly simulate full scale installation of the strips into the slopes, the reinforcing strips must be driven while spinning the centrifuge at the desired g-level. A remotely controlled miniature mandrel driver was used, and the driving forces were monitored using a compression load cell. A typical plot of driving force required to drive three mandrels in the model slope and the displacement of the top surface of the crest is shown in Figure 10. A driving force of about 85 kgf is required to drive the three mandrels (4, 5 and 6) in the 15.24 cm (6 in) high model slope at 15-g, simulating an installation into a 2.3 meter high full prototype slope. The displacement of the top surface of the slope indicates a minor heave of the top surface during insertion of the mandrel and settlement immediately upon retrieval of the mandrel.

This indicates that the driving mechanism used in this study is appropriate and causes minor disturbance to the slope during installation. This observation is critical in designing actual driving mechanisms.

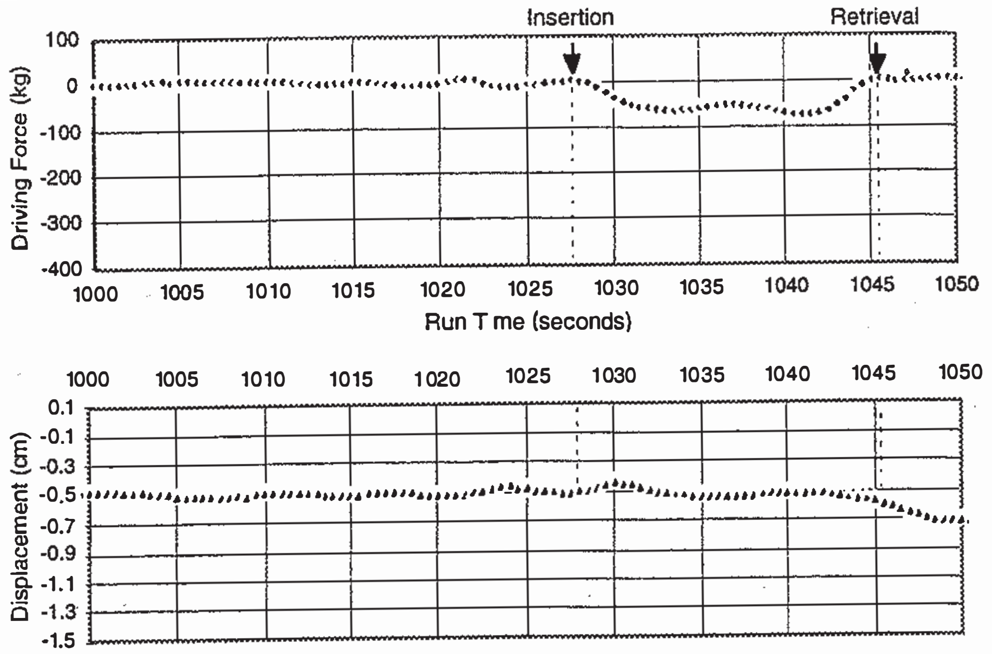


Figure. 10 Typical plot of driving force and displacement of the top of the slope versus time (negative values indicate compressive driving force and downward displacement, respectively)

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 the completion of the installation operation.

6 CONCLUSIONS

The instrumentation used in this study yielded reliable data which can be used to justify the feasibility of the proposed method of slope reinforcement. Although geotextile strain gage measurements do not indicate the actual average strains, the values are quite consistent and can be calibrated to yield actual strains of the reinforcing elements.

The results from these model tests provide useful information for the design of the spacing and placement of the reinforcing strips, and the design of the actual prototype driving equipment. The tests performed herein show the feasibility of the proposed method of insitu slope reinforcement. The driving mechanism employed in the study was very practical, and a similar concept may be adopted in the actual design of the prototype drivers. The results can also be used to verify the practicality and the economy of this proposed mechanically stabilized earth system.

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