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FAILURE OF STEEP REINFORCED SOIL SLOPES

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ABSTRACT

A centrifuge study was undertaken to investigate the failure mechanisms of geosynthetically reinforced steep soil slopes and to evaluate the assumptions in their design. The selected variables in the testing program were the reinforcement spacing, soil strength, and reinforcement strength. Failure in the models was characterized by well-defined shear surfaces through the toe of the slope. The moment of failure was defined by a sudden change in the rate of settlements at the crest of the slope, as monitored from transducers placed on top of the centrifuge models. Well-defined failure surfaces developed, which is in good agreement with current design methods for reinforced slopes based on limit equilibrium. Interpretation of the failure mechanisms in reinforced soil slopes also depends on the distribution of reinforcement forces with depth. However, in contrast to the current design assumptions that failure should initiate at the toe of the reinforced slopes, failure of all centrifuge slope models was observed to initiate at midheight of the slopes.

INTRODUCTION

Centrifuge testing provides a tool for geotechnical modeling in which prototype earth structures can be studied as scaled-down models while preserving prototype stress states. The principle of centrifuge testing is to raise the acceleration of the scaled model in order to reach prototype stress levels in the model. The combination of experimental centrifuge modeling results with analytic limit equilibrium predictions is a useful approach to investigate the performance of reinforced soil structures at failure. The investigation of the performance of geosynthetically reinforced soil slopes at failure is of particular interest because reinforced slopes are conventionally designed using a limit equilibrium approach.

Small-scale physical modeling of engineered earth structures has been used in the past to provide insight into failure mechanisms (e.g., Lee et al., 1973; Holtz and Broms, 1977; Juran and

Christopher, 1989). However, a limitation of scaled physical models is that the stress levels in the models are much smaller than in the full scale structures, thus leading to different soil properties and loading conditions. Finite element analyses have also been used to investigate failure mechanisms of reinforced soil structures (e.g., Hird et al., 1990; San et al., 1994). Standard finite element techniques are useful for analysis of structures under working stress conditions. However, modeling of failure in frictional materials requires special techniques to handle the localization of deformations, such as specific continuum formulations or the use of adaptive mesh refinement to capture slip discontinuities (Zienkiewicz and Taylor, 1991).

As part of a research program on the design, construction, and performance of high embankments, the California State Department of Transportation sponsored an extensive centrifuge study aiming at validating current design procedures for geosynthetically reinforced soil slopes (Zornberg, 1994; Zornberg et al., 1995). Limit equilibrium analysis methods have been traditionally used to analyze the stability of slopes with and without reinforcements. However, to date, limit equilibrium predictions of the performance of geosynthetically reinforced slopes have not been fully validated against monitored failures. This has led to uncertainty in their design. Consequently, an investigation was initiated to evaluate the assumptions and selection of parameters for the design of these structures. The results of the centrifuge tests provided an excellent opportunity to examine the validity of various assumptions typically made in the analysis and design of reinforced soil slopes. This paper presents a description of the failure observed in the different models tested as part of this investigation. Subsequent publications will present further evaluation of the failure mechanisms and implications of the results on the design of reinforced soil slopes.

CENTRIFUGE TESTING OF REINFORCED SOIL STRUCTURES

The stress dependent behavior of soils poses a problem when tests on small-scale geotechnical models are performed in the laboratory under a normal gravity field. In some cases, the use of appropriate surface loading can provide reasonable representation of the stresses created by body forces in a prototype structure. However, if body forces are to be properly represented in a model of the entire structure, it is necessary to turn to centrifuge testing.

Besides predicting the performance of prototype structures centrifuge testing can be performed for at least two other important purposes, both of which were of interest in this study:

- *The investigation of failure mechanisms*, in which the centrifuge is used as a tool to induce, in a model structure, levels of stress that are comparable to those usually found in prototypes. Such studies are often used to define new kinematically admissible collapse mechanisms and new statistically admissible stress distributions (Schofield, 1980; Mitchell et al., 1988); and

- *the validation of predictive tools*, in which the centrifuge is used to investigate the ability of numerical or analytical tools to predict the response of the small-scale model under prototype-like levels of stress (Shen et al., 1982; Liang et al., 1984). Simple geometries can be used in the models, and the analyses can incorporate the material properties, stress history, boundary loading conditions, and curved acceleration field that prevail in a centrifuge test.

As any experimental technique in geotechnical engineering, centrifuge testing does not reproduce exactly the conditions at which soil exists in an earth structure. This is due to the non-homogeneity and anisotropy of soil profiles, both in natural deposits and in man-made earth structures, and due to the limitations of the modeling tool. Some of the factors that cause differences between the behavior of model and prototype are: (i) the acceleration field in the centrifuge, which is directly proportional to the radius of rotation in a centrifuge model; (ii) the stress paths in the model, which are not necessarily identical to those of a structure built sequentially in the field; and (iii) the boundary effects, such as friction and adhesion between the walls of the model box and the soil, which can affect the results of the tests designed to represent plane strain conditions. Identification of these effects helps in the selection of model construction procedures that minimize their influence. More importantly, these effects can often be quantified and taken into account in the analytic tools used to evaluate the centrifuge test results.

The principle of centrifuge modeling is based upon the requirement of similarity between the model and the prototype. If a model of the prototype structure is built with dimensions reduced by a factor $1/N$, then an acceleration field of N times the acceleration of gravity, g, will generate stresses by self-weight in the model that are the same as those in the prototype structure. Additional scaling relationships can be determined either by analysis of governing differential equations or by dimensional analysis and the theory of models.

The scaling laws governing the problem under study (i.e. the behavior of cohesionless reinforced soil slopes at failure) were developed by assuming the validity of limit equilibrium. Specifically, similitude requirements which guarantee identical factors of safety in the model and the prototype structures lead to the conclusion that the same soil density and soil friction angle should be used in the model and in the prototype. These conditions can be satisfied by building the model using the same backfill soil used in the prototype structure. However, the scaling factor for the reinforcement tensile strength should be equal to $1/N$, where N is model scale. That is, an Nth-scale reinforced slope model should be built using a planar reinforcement N times weaker than the prototype reinforcement elements (Zornberg et al., 1995).

CHARACTERISTICS OF THE CENTRIFUGE MODELS

All reinforced slope models in this experimental testing program had the same geometry and were built within the same strong box. The models were subjected to a gradually increasing centrifugal acceleration until failure occurred. The centrifuge tests were performed using a Schaevitz centrifuge at the University of California, Davis, designed to apply controlled centrifugal accelerations up to 175 g and with a limit of 4,500 g-kg at a nominal radius of 100 cm (39.4 in.). The payload of the testing package can be up to 45 kg (100 lb).

A strong box with inside dimensions of 419 mm x 203 mm in plan x 300 mm in height (16.5 in x 8 in x 11.75 in) was used to contain the model. A transparent Plexiglas plate on one side of the box enabled a side view of the model during testing. The other walls of the box were aluminum plates lined with Teflon to minimize side friction. The Plexiglas was lined with a mylar sheet overprinted with a square grid pattern, which provided a reference frame for monitoring displacements within the backfill. In order to prevent scratches and to minimize side friction, a second plain mylar sheet was used as a protection sheet. The box was sufficiently rigid to maintain plane strain conditions in the model.

The overall dimensions of the geotextile-reinforced slope models are given as shown in Figure 1 for the case of a model with nine reinforcement layers. The locations of displacement transducers are also indicated in the figure. All models were built with a total height of 254 mm (10 in). They consisted of 228 mm (9 in) high geotextile-reinforced slopes built on a 25 mm (1 in) thick foundation layer. The slope in all models was 1H:2V, and air dried Monterey No. 30 sand was used both as backfill material and foundation soil.

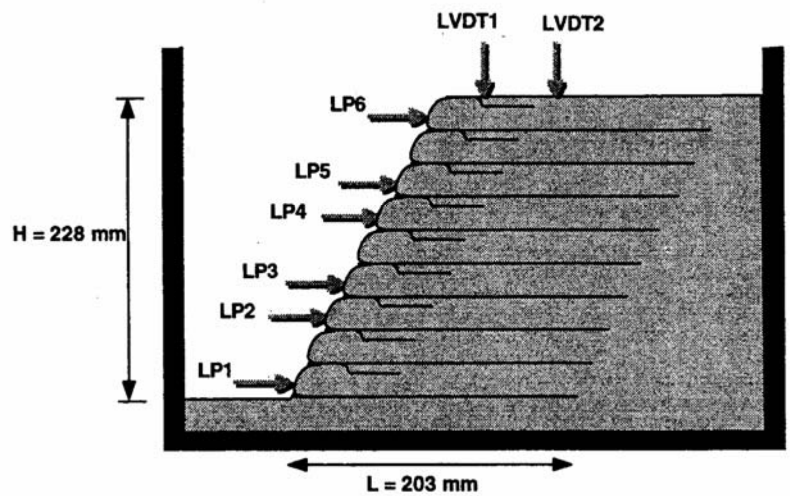

Figure 1 - Centrifuge model with 2.5 cm reinforcement spacing

The number of reinforcement layers in the models varied from six to eighteen, giving reinforcement spacings from 37.5 mm (1.5 in) to 12.5 mm (0.5 in). All models were built using the same reinforcement length of 203 mm (8 in). The use of a reasonably long reinforcement length was deliberate, since this study focused on the evaluation of internal stability against breakage of the geotextile reinforcements. By selecting long enough geotextile reinforcements, external or compound failure surfaces were expected not to develop during testing. The geotextile layers were wrapped at the slope face in all models. Green colored sand was placed along the Plexiglas wall at each level of geotextile reinforcements in order to better identify the location of the potential failure surface. Black colored sand markers were placed at a regular horizontal spacing (25 mm) to monitor lateral displacements within the backfill material.

In order to guarantee consistent soil densities and placement conditions in the reinforced soil models, carefully controlled construction procedures were observed during model preparation. These procedures included sand pluviation through air under controlled discharge rate and discharge height to give uniform backfill relative densities of either 55% or 75%. A vacuum system was used to achieve the target backfill level. A detailed description of the construction procedures of the reinforced slope models is presented in Zornberg et al. (1995).

Six linear potentiometers were used to monitor the lateral displacements of the slope face. The linear potentiometers were supported by an aluminum plate and their location was adjusted for each model so that they were always placed at midheight between two reinforcement layers. Two linear variable displacement transducers (LVDTs) were used to monitor vertical settlement at the crest of the geotextile-reinforced models. Readings from these transducers proved very useful in accurately identifying the moment of failure. One electrical channel was additionally used to record directly the angular velocity (rpm) during centrifuge testing. A television camera, mounted at the center of the rotating structure of the centrifuge, and a video recording device were used as an additional monitoring system. This system provided not only a continuous and instantaneous monitoring of the tests while it was in progress, but also a permanent record of the model tests. A 45° mirror was used to view the model in-flight through the Plexiglas side wall. The recorded images were used to examine the initiation of failure and to identify the probable failure mechanisms.

After construction, the reinforced slope models were weighed and placed in the swing bucket of the centrifuge. Temporary support molds were removed, and both static and dynamic balancing of the rotating arm was performed. A mirror inclined at 45° was placed adjacent to the Plexiglas so that the model could be observed in-flight by the closed-circuit TV camera. Figure 2 shows the view of a model already placed in the swing bucket. The figure shows a top view of the model and its image through the slant mirror before placement of the displacement transducers. As the arm of the centrifuge spins, the buckets supported by hinged pins swings upward so that the top surface of the model is almost perpendicular to the plane of rotation. The models were subjected to a gradually increasing centrifugal acceleration until failure occurred.

The models were carefully disassembled after failure, and the backfill was vacuumed out and the geotextile reinforcements were retrieved. The retrieved geotextiles were used to evaluate the breakage pattern to locate the failure surface from the observed tears. The retrieved geotextile samples always showed breakage in a direction perpendicular to the direction of loading.

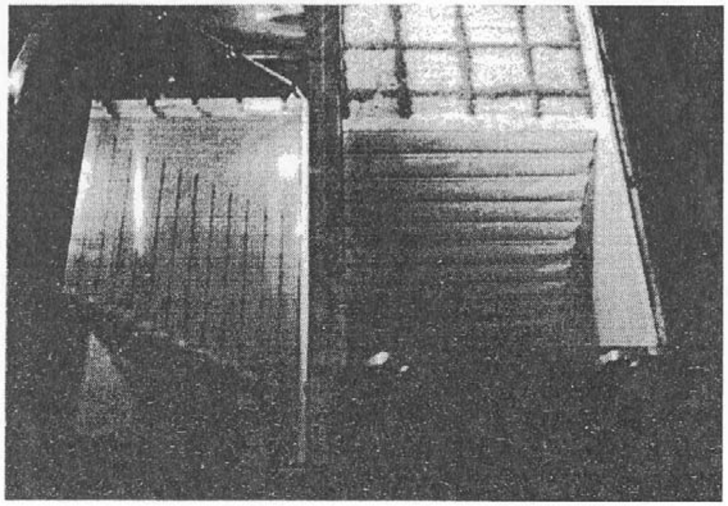

Figure 2 - Top view of Model B12, already placed in the swing bucket, and of its image through the slant mirror.

SCOPE OF THE TESTING PROGRAM

All variables in this testing program were selected so that they can be taken into account in a limit equilibrium analysis framework. Accordingly, the selected variables were:

- Vertical spacing of the geotextile reinforcements: four different reinforcement spacings were adopted;
- soil shear strength parameters: the same sand at two different relative densities was used; and
- ultimate tensile strength of the reinforcements: two geotextiles with different ultimate tensile strength were selected.

All models were built with the same slope and the same total height. The centrifuge tests performed as part of this study can be grouped into three test series, each aimed at investigating the effect of one of the variables:

- Baseline, B-series: performed to investigate the effect of reinforcement spacing. Centrifuge models with six, nine, twelve, and eighteen reinforcement layers were used in this series. Monterey No. 30 sand at 55% relative density and the weaker geotextile were used in all the models in this series.
- Denser soil, D-series: performed to investigate the effect of soil strength parameters on the stability of geotextile-reinforced slopes. A denser backfill (Monterey No. 30 sand at

75% relative density) than in the B-series was used. The geotextile used as reinforcement was the same as in the B-series.

- Stronger geotextile, S-series: performed to investigate the effect of geotextile ultimate tensile strength on the performance of reinforced slopes. These models were reinforced with a geotextile stronger than the one used in the other series. As in the B-series, Monterey No. 30 sand at 55% relative density was used as backfill material.

Each reinforced slope model in this study was named using a letter that identifies the test series (B, D, or S), followed by a numerical value that indicates the number of reinforcement layers used in the model. For example, Model B12 is the reinforced slope model from the B-series (Baseline), reinforced using twelve geotextile layers.

CHARACTERISTICS OF THE FAILURE SURFACES

Baseline B-series

All models in this series were tested using the same backfill density and the same geotextile fabric, but different reinforcement spacing. Typical results obtained after centrifuge testing of one of the models from the Baseline series (model B18) are presented in order to illustrate the type of data which was obtained throughout the study. The history of centrifugal acceleration during centrifuge testing of model B18 is shown in Figure 3. The acceleration was increased until sudden failure occurred after approximately 50 min of testing when the acceleration imparted to the model was 76.5 times the acceleration of gravity.

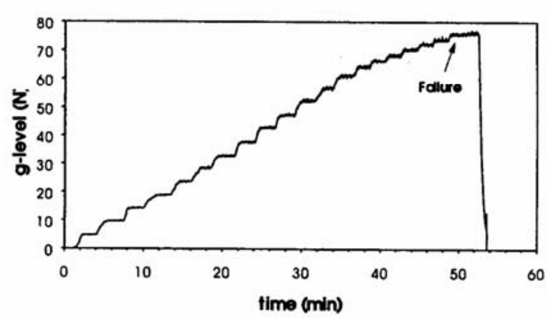

Figure 3 - G-level (N) versus time during centrifuge test of Model B18

Failure development in the reinforced slope could be identified from the TV images. However, settlements at the crest of the slope, monitored by LVDTs, proved to be invaluable to more accurately identify the moment of failure. The increasing settlements at the top of the reinforced slope during centrifuge testing was monitored at 12.5 mm (0.5 in.) and 62.5 mm (2.5 in.) from the crest of the slope. A sudden increase in the monitored settlements indicated the moment of failure when the reinforced active wedge slid along the failure surface. Recorded images showing failure development of the models were an effective way of identifying the actual shape of the failure surface and the possible failure mechanisms. Figure 4 shows the failure surface that developed in model B18, as observed after unloading the model from the centrifuge bucket. As can be seen, the failure surface is clearly defined and goes through the toe of the reinforced slope.

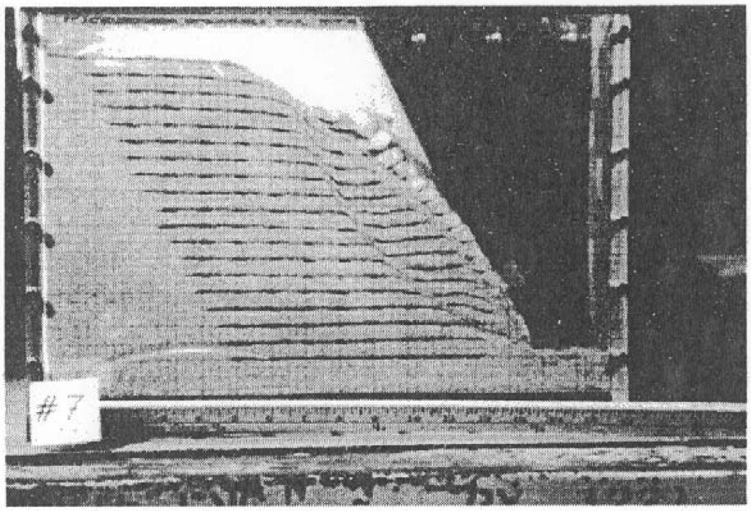

Figure 4 - View of model B18 after the centrifuge test

Figure 5 shows one of the geotextile layers retrieved from model B18 after centrifuge testing (fourth layer from the base of the slope). Since this particular layer was located towards the base of the slope, the failure surface intersected both the primary reinforcement layer and the overlapping length. Figure 6 shows the eighteen geotextiles retrieved after centrifuge testing of model B18. The geotextile shown at the top left corner of the figure is the reinforcement layer retrieved from the base of the reinforced slope model. The geotextile at the bottom right corner is the reinforcement retrieved from the top of the model. All retrieved geotextiles show clear breaks at the location of the failure surface. The pattern observed from the retrieved geotextiles shows that internal failure occurred when the reinforcements reached their tensile strength. The geotextile layers located towards the base of the slope model also showed breakage of the geotextile overlaps, which indicates that overlapping layers clearly contributed to the stability of the slope. No evidence of pullout was observed, even on the short overlapping layers.

The tears in the geotextile reinforcements were always perpendicular to the direction of loading, showing no evidence of edge effects caused by lateral friction between the model and the walls of the centrifuge box. If side friction had significant influence, the shape of the geotextile tears would have been expected to be curved. Additional evidence that edge effects were small was obtained by dissecting one of the models (model B6) after centrifuge testing. To preserve the model, apparent cohesion was added to the initially dry sand by wetting the backfill after centrifuge testing. Dissection of the model was then performed in order to compare the pattern of displacements observed through the Plexiglas wall with those at the center of the model. Displacements observed within the model and at the interface with the Plexiglas wall were essentially identical.

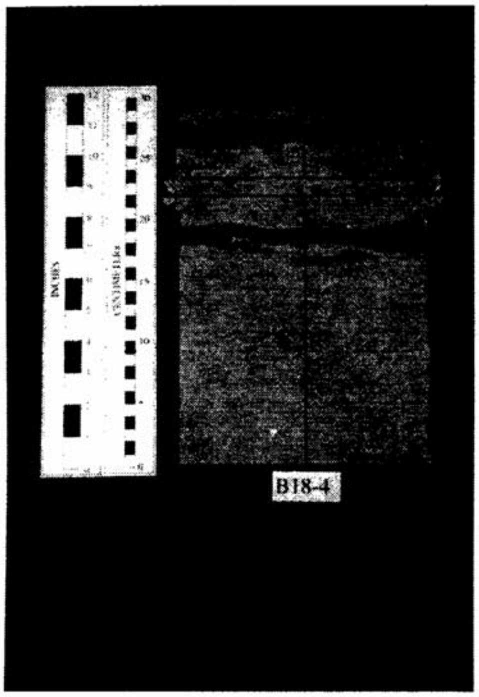

Figure 5 - Geotextile layer retrieved from model B18, showing tensile tears along the primary reinforcement and overlapping layers

The location of the failure surface could be determined after the test by measuring the location of the tears in the retrieved geotextile primary reinforcements and overlaps. Figure 7 shows the location of the failure surface for model B18, as measured from the retrieved geotextiles. The figure also shows the location of the failure as digitized from the video images recorded at the moment of failure during the test. The top layers of the models were outside the range of view of the images observed with the TV camera. There is a clear agreement between the two sets of experimental data used to estimate the location of the failure surface in the reinforced slope model. This good agreement is further evidence that edge effects during centrifuge testing were negligible.

Denser soil D-series

Models in this series had the same reinforcement layout and reinforcement tensile strength as the models in the B-series, but built using Monterey No. 30 sand at a higher relative density (75%). Figure 8 shows one of the models in this series, model D12, already placed in the centrifuge bucket and ready for testing. Catastrophic failure also occurred in this test. Figure 9 shows the failed model D12 after centrifuge testing. A clearly defined failure surface through the toe of the slope was also observed in all models from the D-series. Geotextile reinforcements were also retrieved from the models tested in the D-series. As was also the case for the models tested in the Baseline series, clear breakage of the reinforcements occurred in these models at the location of the failure surface, without any evidence of pullout.

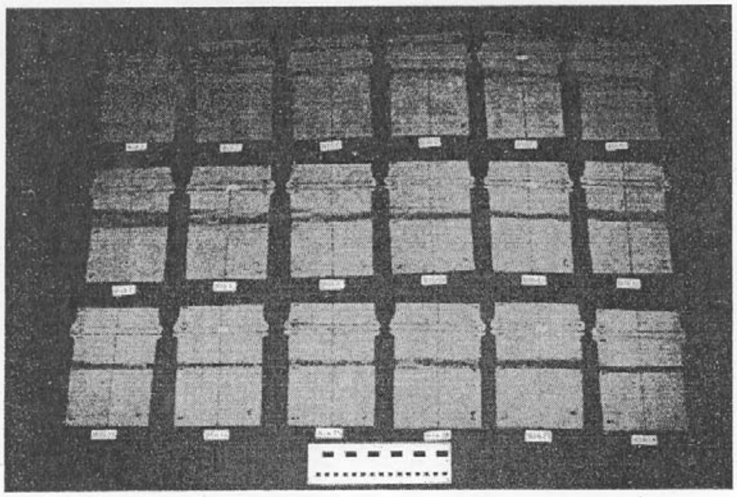

Figure 6 - View of model B18 after the centrifuge test

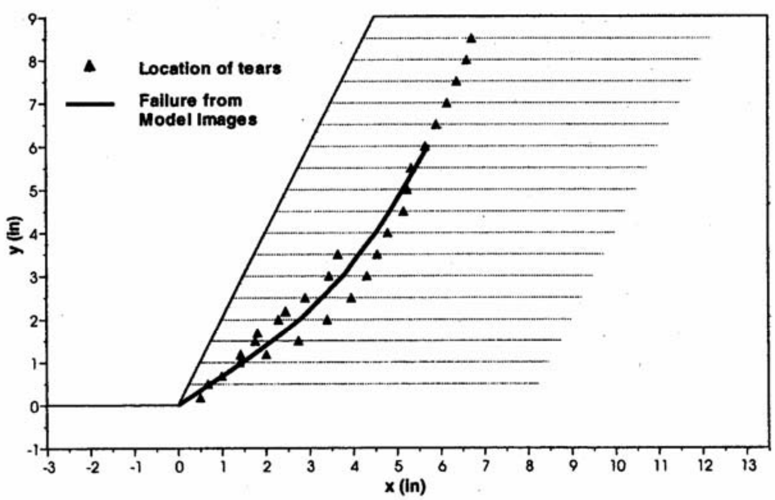

Figure 7 - Location of the failure surface for centrifuge model B18, as obtained from tears in the reinforcements and from images recorded through the Plexiglas wall

Denser soil D-series

Models in this series had the same reinforcement layout and reinforcement tensile strength as the models in the B-series, but built using Monterey No. 30 sand at a higher relative density (75%). Figure 8 shows one of the models in this series, model D12, already placed in the centrifuge bucket and ready for testing. Catastrophic failure also occurred in this test. Figure 9 shows the failed model D12 after centrifuge testing. A clearly defined failure surface through the toe of the slope was also observed in all models from the D-series. Geotextile reinforcements were also retrieved from the models tested in the D-series. As was also the case for the models tested in the Baseline series, clear breakage of the reinforcements occurred in these models at the location of the failure surface, without any evidence of pullout.

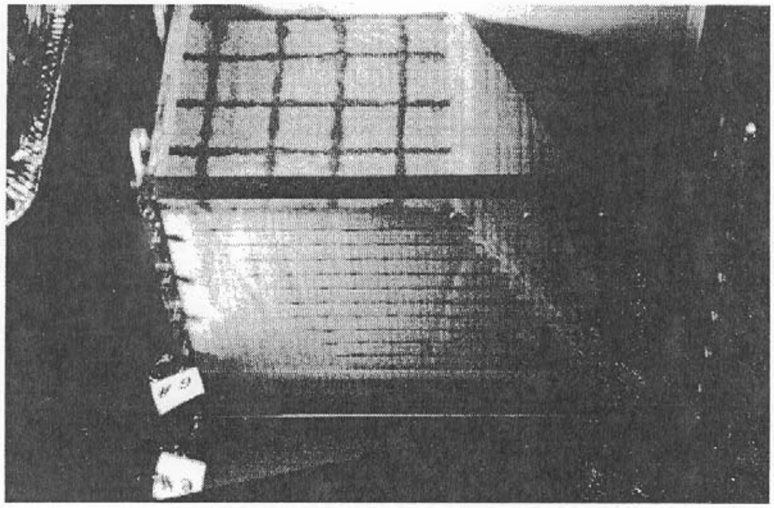

Figure 8 - Model D12 ready for testing

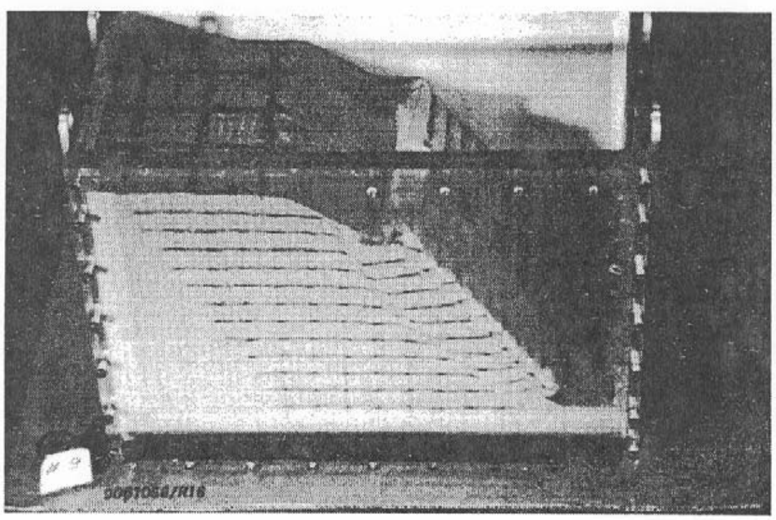

Figure 9 - Model D12 right after the test

Stronger Geotextile S-Series

The geometry, reinforcement layout, and backfill density in this series were identical to models in the B-series, but a geotextile with a higher tensile strength was used. Figure 10 shows the failure surface that developed in model S9 after testing. The photograph shows that the failure zone is slightly wider than the one observed in models built using the weaker geotextile. Although models reinforced using the stronger geotextile also failed along a clearly defined surface, they did not exhibit the sudden collapse observed in the failure of models built using the weaker fabric. This can be explained by results from tensile tests which show that the stronger geotextile reinforcement, differently than the weaker fabric, large strains after reaching the ultimate tensile strength.

The geotextile reinforcements retrieved after the tests showed severe straining at the location of the failure surface. However, complete separation breakage did not occur as in the models built using the weaker fabric. The tears and the magnitude of the permanent deformations in the geotextiles indicate that, also in this case, the reinforcements did reach their ultimate strength. Again, no evidence of pullout was observed and the overlaps towards the base of the models worked as additional reinforcements.

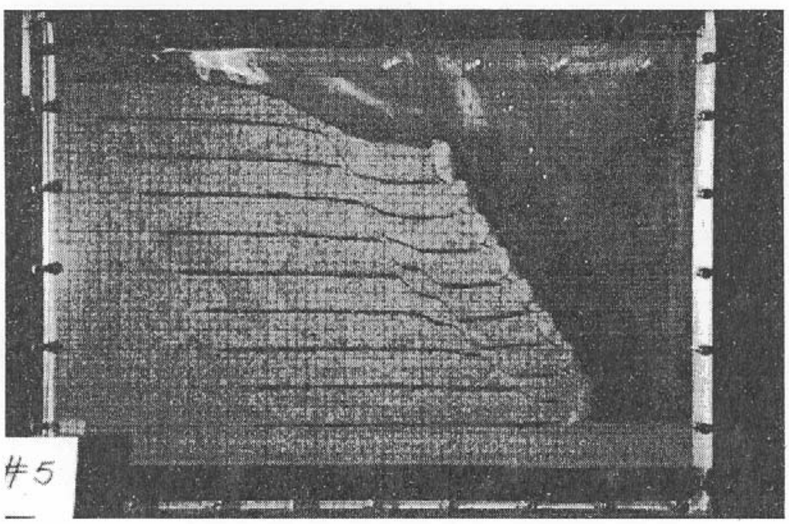

Figure 10 - Model S9 after testing

DEVELOPMENT OF THE FAILURE SURFACES

As already described, failure of all the models in this study was characterized by the development of a well-defined shear surface approximately through the toe of the slope. The moment of failure, defined by a sudden change in the rate of settlements at the crest of the slope, was found to agree very well with the visual observation of the initiation of failure through the Plexiglas wall of the models.

Some differences in the development of failure were observed in the different test series. In the B-series, the time elapsed between initiation of failure and the final collapse of the model was relatively short. After initiation of failure, collapse generally occurred without an additional increase of the g-level. The time elapsed between initiation of failure and structure collapse appeared to be even shorter in the D-series tests. This may be attributed to a more rapid drop in strength in the denser backfill after it reaches peak strength. The time elapsed between initiation of failure and final structure collapse for the models built using a stronger geotextile (S-series) was greater than for the models in the other test series. Although the initiation of failure could be estimated with accuracy, and the failure surface was well defined, the moment of final structure collapse was more difficult to identify than in the other series. The post-failure performance may be attributed to the large displacements that the stronger fabric is able to sustain after reaching its ultimate tensile strength. This behavior was also observed in unconfined geotextile tensile tests, and is different from that of the weaker geotextiles, which shows a rapid drop in tensile strength after the peak. Thus, it appears that the post-failure behavior of the slope models until final structure collapse depends on the post-peak behavior of the backfill soil and, mainly, of the geotextile reinforcements.

Figure 11 shows the in-flight view of one of the models (model B12) at the moment of failure initiation during centrifuge testing. This image corresponds to the moment of failure defined by the transducers that monitored the settlements at the crest of the model. The image was recorded using the TV camera located inside the centrifuge. Careful study of the figure shows that the initiation of failure occurred approximately in the middle of the slope. This can be observed by kinks in the horizontal colored sand layers that were placed during construction at the levels of the reinforcements. The kinks initially appeared at approximately the midheight of the slope, and then failure rapidly extended to the reinforcement layers in the upper half of the model. The lower geotextile layers showed no evidence of kinking until the moment of ultimate structure collapse. The development of failure observed in the centrifuge slope models indicates that the lower reinforcement layers were not the ones to first reach failure. The same pattern of behavior was observed for the remaining reinforced soil models. Current design methodologies assume that the reinforcement tension distribution with depth is triangular with maximum tension at the base of the slope. This distribution implies that a progressive failure mechanism should start at the toe of the reinforced slope for uniformly spaced reinforcements of equal strength, which is inconsistent with the observed behavior.

Figure 12 shows the final collapse of model slope B12 as recorded in-flight during centrifuge testing. There is a very good agreement between the location of the failure surfaces obtained from the images on the Plexiglas wall and from the measurements of the geotextile reinforcement tears for all the tested models.

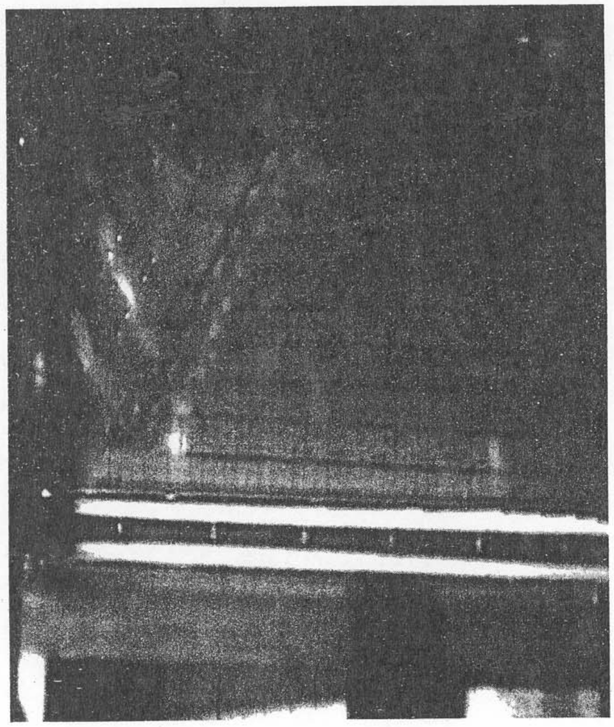

Figure 11 - Initiation of failure in Model B12

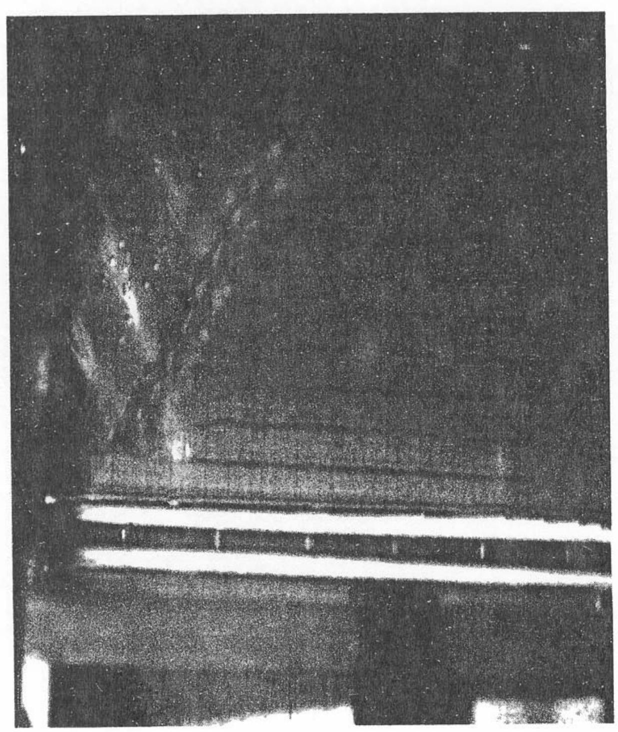

Figure 12 - Final collapse of Model B12

Because internal monitoring of the reinforcement strains was not possible due to the fragility of the geotextiles, direct observation was used instead. In order to verify the location of failure initiation, the testing progress for one of the centrifuge models (model D6) was stopped right after failure initiated, as monitored by the displacement transducers, but before final collapse. The common testing procedure, followed in all the other models, was to continue the test until collapse. Analysis of the retrieved geotextiles from model D6 confirmed that failure started at the middle of the slope height. While reinforcements in the upper half of the model showed the development of tears, the reinforcements in the lower half of the model showed only evidence of straining at the location of the failure surface. Straining was even difficult to identify in the lower geotextile layers. An additional piece of evidence that the reinforcement force distribution is not triangular, as commonly assumed in design, is the fact that the first geotextile layer (at the base of the slope) in all models did not show either tears or evidence of straining.

IMPLICATIONS FOR REINFORCED SLOPE DESIGN

The development of a well-defined failure surface is in good agreement with current design methods for reinforced slopes, which are based on limit equilibrium. The observed failure surfaces can be easily approximated by circular, log spiral, or bilinear surfaces which are conventionally used in the design of geosynthetically reinforced soil slopes.

Interpretation of the failure mechanisms in reinforced soil slopes also depends on a correct evaluation of the distribution of reinforcement forces with depth. From this distribution, the location of the first reinforcement that achieves its ultimate tensile strength can be identified. Current design methods for reinforced soil walls are based on assuming that reinforcement forces are proportional to the overburden pressure from the top of the wall. The rationale behind this assumption is that extensible reinforcements should resist the active earth pressure (Mitchell and Christopher, 1990). Although foundation stiffness has been found to affect the development of force in the lower reinforcement layers, field studies have shown that maximum tensile forces are well predicted by assuming a Rankine active condition in geosynthetically reinforced vertical walls.

In the case of reinforced soil slopes, which have their design based on limit equilibrium and not on working stress methodologies, the reinforcement force distribution with depth must also be assumed. By extending the observations gathered for the case of reinforced soil walls, triangular reinforcement tension distribution increasing proportionally with the depth below the slope crest has been assumed for reinforced soil slopes. This assumption is used in design charts that have been implemented based on limit equilibrium analysis of geosynthetically reinforced soil slopes (Schmertmann et al., 1987; Leshchinsky and Boedeker, 1989; Jewell, 1991). Current FHWA design method for reinforced soil slopes also recommends tensile forces distribution directly proportional to depth below the slope crest for the case of slopes higher than 6 m (Christopher et al., 1990).

However, since failure of the models initiated at mid-height of the slope, the conventional triangular distribution of reinforcement forces with depth is not supported by the experimental results obtained in this study. This has major implications for design, since vertical spacing and ultimate strength of the reinforcements are currently selected considering the most critical zone is at the base of the structure.

The centrifuge test results indicate that failure does not start at the toe of the slope and, consequently, that the reinforcement with maximum tension is not located at the base of the slope. It appears that the maximum reinforcement tension with depth depends on the slope of the reinforced soil structure, and that for the 1H:2V centrifuge slope models the location of maximum reinforcement tension occurs at midheight of the slope. The distribution of maximum reinforcement tension with depth measured from well instrumented 1H:2V geogrid- and geotextile-reinforced slopes (Adib, 1988; Christopher et al., 1992) also indicate that the maximum reinforcement tension is not at the base of the slope, but approximately at midheight of the structure. A reassessment of the local equilibrium between reinforcement forces and working soil stresses may provide further insight into the possible reinforcement force distribution for reinforced soil slopes.

SUMMARY AND CONCLUSIONS

Limit equilibrium analysis methods have been traditionally used to analyze the stability of reinforced soil slopes. The accuracy of these methods depends on whether the assumed mode of failure adequately represents the conditions actually leading to the collapse of the structure. However, to date, limit equilibrium predictions of the performance of geosynthetically reinforced slopes have not been fully validated against monitored failures. Consequently, a centrifuge study was undertaken to investigate the performance of geosynthetically reinforced steep soil slopes at failure and to evaluate the assumptions in their design. This paper presents a description of the failure observed in the different models tested as part of this investigation.

Failure in the models was characterized by well-defined shear surfaces through the toe of the slope. The moment of failure was defined by a sudden change in the rate of settlements at the crest of the slope, as monitored from transducers placed on top of the centrifuge models. This moment of failure was found to agree very well with the visual observation of the initiation of failure in the models. The development of a well-defined failure surface is in good agreement with current design methods for reinforced slopes, which are based in limit equilibrium.

Interpretation of the failure mechanisms in reinforced soil slopes depends on the distribution of reinforcement forces with depth. From this distribution, the location of the first reinforcement that achieves its ultimate tensile strength can be identified. However, in contrast to the current design assumptions that failure should develop from the toe of the reinforced slopes, failure of all centrifuge 1H:2V slope models was observed to initiate at midheight of the slopes. These results suggest that the reinforcement tension distribution with depth is not triangular with the maximum tension at the base of the slope. Instead, the test results suggest that the distribution of tension in the reinforcements with depth depends on the slope of the reinforced soil structure.

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