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Testing of Reinforced Slopes in a Geotechnical Centrifuge

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ABSTRACT: An evaluation of the use of centrifuge modeling as a tool for analyzing the behavior of reinforced soil slopes is presented in this paper. A review of the state-of-the-art indicates that previous centrifuge studies have focused mainly on the performance of reinforced soil vertical walls and that limit equilibrium approaches (used in the design of reinforced soil slopes) have not been fully validated against the failure of models in a centrifuge. As part of an evaluation of the conditions of similarity governing the behavior of reinforced soil structures at failure, scaling laws are specifically derived by assuming the validity of limit equilibrium. It is demonstrated that an Nth-scale reinforced slope model should be built using planar reinforcements having $1/N$ the strength of the prototype reinforcements in order to satisfy similarity requirements. A description of the experimental testing procedures implemented as part of a recent centrifuge testing program is presented, and an example dataset from this investigation is used to illustrate typical results. These include the g-level at failure, visual observation of failure development, and post-failure analysis of reinforcement breakage. The pattern observed in the geotextile reinforcements retrieved after testing indicates that the boundary effects were negligible.

KEYWORDS: centrifuge testing, soil reinforcement, state-of-the-art review, geosynthetics, geotextiles, scaling laws, failure

A wide range of geotechnical problems can be investigated using centrifuge physical modeling techniques (Corte 1988; Ko and McLean 1991; Leung et al. 1994), and evaluation of the behavior of reinforced soil structures is no exception. The purpose of this paper is to present an evaluation of the use of centrifuge modeling as a tool for analyzing the behavior of reinforced soil slopes. This evaluation includes: (1) a state-of-the-art review on the centrifuge modeling of reinforced soil structures; (2) a derivation of the conditions of similarity specific for the problem under study; and (3) a description of the experimental testing procedures implemented as part of a recent centrifuge study undertaken to evaluate the performance of geotextile-reinforced slopes at failure.

Small-scale physical modeling of reinforced soil structures tested at the acceleration of gravity (1 g) has been used in the past to provide insight into failure mechanisms (Lee et al. 1973; Holtz and Broms 1977; Juran and Christopher 1989; Palmeira and Gomes 1996). However, a limitation of reduced-scale 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. The use of finite element analyses has also been used to investigate failure mechanisms of reinforced soil structures (Hird et al. 1990; San et al. 1994). However, while standard finite element techniques are useful for analysis of structures under working stress conditions, 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).

Centrifuge testing provides a tool for geotechnical modeling in which prototype structures can be studied as scaled-down models while preserving the stress states (Avgherinos and Schofield 1969). The principle of centrifuge testing is to raise the acceleration of the scaled model in order to obtain prototype stress levels in the model. Although modeling limitations are often difficult to overcome when seeking a direct comparison between the performance of centrifuge models and full-scale prototype structures, many of these limitations can be avoided when the purpose is to validate analytic or numerical tools. Thus, 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.

As part of a research program on the 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 a perceived over-conservatism in their design. Consequently, an investigation was undertaken to evaluate the assumptions and selection of parameters for the design of these structures. Detailed interpretation of the experimental results obtained in this investigation and of the suitability of limit equilibrium as a basis for design are given elsewhere (Zornberg et al. 1995) and will be presented further in subsequent publications. After presenting a state-of-the-art review on centrifuge modeling of reinforced soil structures and the derivation of the scaling laws, this paper describes the experimental setup used in the aforementioned centrifuge investigation undertaken to evaluate the performance of reinforced soil slopes at failure.

Review of Previous Centrifuge Studies of Reinforced Soil Structures

A summary of the main aspects of previous centrifuge studies performed to investigate the behavior of reinforced soil structures

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is listed in Table 1. Some of the earliest tests were performed by Bolton et al. (1978) and Bolton and Pang (1982) on vertical wall models of dry sand reinforced using metallic strips and rods. They suggested a "simple anchor theory" for design of reinforced soil walls based on active pressures exerted on the facing area attributable to a strip. The vertical stresses used to compute the active pressures included a contribution from the overturning effect of the backfill. Their main conclusions were that the distribution of vertical stress under the reinforced soil mass was close to being uniform, and that the use of the active earth pressure coefficient underestimated the acceleration at failure in the wall models.

Centrifuge tests at the LCPC (Nantes, France) were performed on 600-mm-high geotextile-reinforced walls with five or six layers of reinforcement, tested at 15 *g* to represent a 9-m-high prototype (Blivet et al. 1986; Matichard et al. 1988). A vertical surcharge was applied in-flight in order to investigate the performance of bridge abutments. Although up to 10% strain was recorded in one test, rupture was not achieved at this level of deformation.

Centrifuge tests were performed using the geotechnical centrifuge at the University of California, Davis, to investigate the performance of reinforced soil vertical wall models at failure (Mitchell et al. 1988; Jaber 1989). An extensive parametric study investigated the effects of reinforcement extensibility, type of facing, compressibility of foundation, creep of geotextile reinforcement, and surface loading. Orientation of the initial failure surface was observed not to be affected by the type of reinforcement. It was concluded that current design procedures for reinforced soil walls may be conservative since the centrifugal accelerations at which rupture failures occurred were up to twice the values computed assuming that Rankine active pressures develop within the soil mass.

Most centrifuge studies on reinforced soil structures have concentrated on parametric studies and validation of design methods without comparing their results to the behavior of actual prototypes. An exception was the study presented by Jaber et al. (1990), in which the stresses and displacements of four centrifuge models were compared to those measured on four similar full-scale soil walls. The 500-mm-high models were tested at 12 *g* on the large beam centrifuge at the University of California, Davis. A variety of reinforcements was used, including bar mats, steel strips, geogrids, and nonwoven geotextiles, each instrumented with strain gauges. Reinforcement tensions showed good agreement between models and prototypes, lending credibility to the centrifuge modeling technique for the study of reinforced soil structures. The out-

TABLE 1—*Previous centrifuge studies on the performance of reinforced soil structures.*

Structure	Reinforcement Type	Height, mm	Centrifuge Location	Analytic Method Used for Prediction of Failure	Reference
Reinforced walls	Metallic strips and rods	200	Manchester, U.K.	Simple anchor method	Bolton et al., 1978
Soil nailed walls	Nails	150	U.C. Davis	Limit equilibrium of nailed wall	Shen et al., 1982
Reinforced walls	Metallic strips and rods	200	Manchester, U.K.	Simple anchor method	Bolton & Pang, 1982
Reinforced walls	Nonwoven geotextile	600	LCPC, France	Models did not reach failure	Blivet et al., 1986; Matichard et al., 1988
Reinforced walls	Aluminum foil; plastic strips; nonwoven; plastic grids	150	U.C. Davis	Tie-back type analysis	Mitchell et al., 1988; Jaber, 1989
Reinforced walls and slopes	Nonwoven geotextile	100	Tsukuba, Japan	Simplified stability analysis (Fellenius)	Taniguchi et al., 1988
Embankments on soft ground	Nonwoven geotextile	up to 48	Yokosuka, Japan	Simplified stability analyses (Fellenius)	Terashi & Kitazume, 1988
Reinforced walls	Aluminum foil strips	144; 80	U. of Maryland	Dimensionless safety index	Goodings & Santamarina, 1989
Reinforced walls	Steel strips, steel mesh, geogrid; nonwoven	500	U.C. Davis	Models did not reach failure	Jaber et al., 1990; Jaber, 1989
Reinforced wall	Aluminum strips	500	U.C. Davis	Global safety against reinforcement rupture	Jaber & Mitchell, 1990; Jaber, 1989
Reinforced walls	Nonwoven geotextile	114 to 191	U. of Maryland	Failure prediction not reported	Goodings, 1990
Reinforced walls	Wire mat	150	U.C. Davis	Yield acceleration of sliding block (seismic study)	Kutter et al., 1990; Casey et al., 1991
Anchored walls	Steel anchors	280	Manchester, U.K.	Pullout capacity of anchors	Craig et al., 1991
Embankments on soft ground	Geotextile	100	China	Semi-empirical bearing capacity	Liu et al., 1991
Reinforced walls	Aluminum strips	200	Boulder	Tie-back type analyses	Yoo & Ko, 1991
Reinforced walls	Steel strip	300	RPI	Failure prediction not reported	Ragheb & Elgamal, 1991
Reinforced wall	Woven geotextile	240	China	Model did not reach failure	Shi & Sun, 1992
Reinforced walls	Nonwoven geotextile	190	U. of Maryland	Failure prediction not reported	Güler & Goodings, 1992
Reinforced walls and slopes	Geogrid?	150	Japan	Stability analysis using planar surface	Abe et al., 1992
Reinforced walls	Nonwoven geotextile	550	LCPC, Nantes	Failure prediction not reported	Matichard et al., 1992a; 1992b
Reinforced walls	Nonwoven geotextile	590	Boulder	Failure prediction not reported	Law et al., 1992
Soil nailed walls	Nails	152	RPI	Seismic study	Tufenkjian & Vucetic, 1992
Reinforced walls and slopes	Nonwoven geotextile	152	U. of Maryland	Stability analysis using Bishop	Porbaha & Goodings, 1994; 1996; Porbaha, 1996
Soil nailed walls	Nails	up to 150	Israel	Pullout capacity of nails	Frydman et al., 1994
Reinforced walls	Woven geotextile	150	Cambridge, U.K.	Failure prediction not reported	Springman & Balachandran, 1994
Embarkments on soft clay	Geotextile; geogrid	≈150	Cambridge, U.K.	Models did not reach failure	Bolton & Sharma, 1994

ward movements in the centrifuge models were smaller than those observed in the corresponding prototypes.

In addition, a wall model reinforced with aluminum strips was specifically underdesigned so as to collapse (Jaber and Mitchell 1990). The stresses measured in the reinforcements seemed to indicate that significant stress redistribution occurred within the wall near failure, which may explain the overconservatism of current design methods for reinforced soil walls. A simple design approach for internal stability based on a global factor of safety against reinforcement rupture was proposed, which accounts for stress redistribution within the wall. This approach was able to correctly predict the failure of reinforced soil model walls described by Mitchell et al. (1988).

A comprehensive investigation was undertaken at the University of Maryland to evaluate the effect of backfill characteristics and foundation soils on the performance of reinforced soil structures. Goodings and Santamarina (1989) examined the effect of foundation soil and retained fill on the behavior of reinforced soil walls using centrifuge modeling. They observed that the effect of the retained soil on the overall stability of the walls was small, and that soft foundations led to superior wall performance. The behavior of geotextile-reinforced walls using cohesive backfill soil instead of conventional granular material was investigated by Goodings (1990). She concluded that cohesive soils can be successfully used to construct reinforced walls, and that failure of the reinforced soil models occurred always by geotextile breakage and never by pullout. Porbaha and Goodings (1994) reported results of additional tests performed to investigate the behavior of geotextile-reinforced walls and slopes using cohesive backfill founded on weak soils. They found that longer reinforcement improved the structure performance, and that excessive deformations or failure were caused by geotextile rupture or straining, without evidence of pullout. Additional test results and stability analyses presented by Porbaha and Goodings (1996) indicated that the development of tension cracks in the kaolin backfill used in the models led to stress concentrations in the geosynthetics. Also using centrifuge modeling, Güler and Goodings (1992) investigated the use of lime stabilization to improve the properties of clayey backfills. The use of lime was found to substantially improve wall stability even when the geotextile length was only one half of the wall height. An additional evaluation of the behavior of geotextile-reinforced walls backfilled with lime-treated cohesive soil was recently reported by Porbaha (1996). The addition of 2% lime to the backfill significantly improved the prototype equivalent failure height. The factor of safety estimated by limit equilibrium was closer to one for models that showed close agreement between the locations of actual and predicted failure surfaces.

Several of the studies summarized in Table 1 focused on the performance of reinforced soil structures in which deformations or failure were triggered by mechanisms other than self-weight. Among them, Taniguchi et al. (1988) investigated the performance of reinforced soil models that were either tilted in order to simulate lateral acceleration during an earthquake or subjected to a surcharge loading applied behind the wall crest. Smaller displacements were obtained in models with longer reinforcements. The performance of bar mat reinforced walls subject to seismic excitations was investigated by Kutter et al. (1990) and Casey et al. (1991). Yield accelerations obtained from the experimental results were found to be lower than those determined using conventional sliding block models. Ragheb and Elgamal (1991) investigated the effect of deteriorated metallic strip reinforcements on the performance of reinforced soil walls. They found that a strong interlocking in the facing panels attached to deteriorated strips was effective in delaying or even preventing wall failure. A series of 1/5 scale reinforced wall models were brought to failure by applying a vertical surcharge (Law et al. 1992). The centrifuge results were compared with the collapse load obtained in a full-scale prototype loaded to failure. The performance of a series of wall models reinforced with metallic strips subjected to self weight loading and to vertical surcharge to simulate bridge abutments was also reported by Yoo and Ko (1991). Matichard et al. (1992a, 1992b) reported centrifuge test results on the behavior of a geotextile-reinforced abutment loaded on top until failure. Their experimental results showed qualitative agreement with the results from a full-scale prototype test in which failure occurred by breakage of the upper geotextile reinforcements and pullout of the top layer. Springman and Balachandran (1994) investigated the behavior of two wall models reinforced using woven geotextiles and loaded with a strip surcharge. Maximum tension in the reinforcements under working stress conditions agreed with predicted values.

For completeness, Table 1 also includes information on centrifuge studies done to investigate the performance of soil-nailed walls (Shen et al. 1982; Tufenkjian and Vucetic 1992; Frydman et al. 1994), anchored walls (Craig et al. 1991), and embankments over soft foundations (Terashi and Kitazume 1988; Liu et al. 1991; Bolton and Sharma 1994).

Two main observations can be drawn from the evaluation of previous centrifuge studies of the performance of reinforced soil structures: (1) the majority of previous works focused on the performance of vertically faced reinforced walls; and (2) limit equilibrium approaches have rarely been used to predict the failure of centrifuge models.

Instead of focusing on the validation of analytic tools, some of the previous studies focused on evaluating experimentally the effect of different design variables on the g-level at failure (Goodings and Santamarina 1989), while others investigated the performance of models at working stress conditions without reaching failure (Jaber et al. 1990). Among those studies in which failure conditions were used to validate analytical tools, the methods generally used were semi-empirical procedures currently used for reinforced wall design (Bolton and Pang 1982; Mitchell et al. 1988). However, the working stress design methods used for the design of reinforced vertical walls are not generally used for the design of reinforced soil slopes, which is generally based on limit equilibrium approaches. There is, consequently, a lack of experimental data suitable for validating design procedures for reinforced soil slopes.

Purposes and Limitations of Centrifuge Testing

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 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 small-scale model, it is necessary to turn to centrifuge testing.

Besides predicting the performance of prototype structures, centrifuge testing can be used for at least two other important purposes:

- *The investigation of failure mechanisms*, in which the centrifuge is used as a tool to induce, in a model structure, stress levels needed to bring a prototype structure to failure. Such studies are often used to identify kinematically admissible collapse mechanisms and statically admissible stress distributions (Schofield 1980; Mitchell et al. 1988).

- *The validation of predictive tools*, in which centrifuge testing is used to investigate the ability of numerical or analytical tools to predict the response of the small-scale model under prototype stress levels (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.

Centrifuge testing does not reproduce exactly the conditions of the soil in a geotechnical 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 leading to differences in the behavior between models and prototypes are:

- *Acceleration field in the centrifuge*, which is directly proportional to the radius of rotation in a centrifuge model. As a consequence, the resulting stress distribution is curved and deviates from the linear stress distribution in a real structure under the acceleration of gravity (1 g).
- *Stress paths in the model*, which are not necessarily identical to those in a prototype structure. For example, compaction effects cannot be replicated in the model, which is constructed at 1 g prior to centrifuging. Moreover, while placement of a compacted soil layer in a prototype induces deformations on the layers underneath the one being placed, the pre-constructed centrifuge model responds in its entirety as it is brought up to scale speed.
- *Boundary effects*, such as friction and adhesion between the walls of the model box and the soil, can affect the results of the tests designed to represent plane strain conditions. Solutions proposed to minimize the deviation from plane strain conditions include the use of wide models and/or the use of procedures to minimize friction at the boundary surface.
- *Scale effects*, caused by the relative size of sand grains between model and prototype, that may introduce a distortion in situations where either geotextiles or the soil no longer behave as a continuum.

Identification of the effects listed above helps in the selection of model construction procedures that minimize their influences. More importantly, these effects can often be quantified and taken into account in the analytic tools used in the interpretation of the centrifuge test results.

Derivation of Scaling Laws

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.

Scaling Laws Governing the Behavior of Reinforced Slopes at Failure

The conditions of similarity for the behavior of geotechnical structures have been often inferred from general scaling relationships such as those indicated in Table 2 (Scott and Morgan 1977). However, the scaling laws governing the problem under study (i.e., the behavior of cohesionless reinforced soil slopes at failure), are derived herein by assuming the validity of limit equilibrium. In this case, similitude requirements are established in order to guarantee identical factors of safety in model and prototype structures. For simplicity, the ordinary method of slices (Fellenius 1936) is considered in the limit equilibrium expressions stated below, which only satisfies equilibrium of moments for a circular failure surface. In this case, the factor of safety is calculated as:

$$FS = \frac{\sum \textit{Moments resisting slope failure}}{\sum \textit{Moments driving slope failure}} \tag{1}$$

For a prototype reinforced cohesionless slope, the factor of safety FS_p can be estimated as (Fig. 1):

$$FS_p = \frac{\sum (A_i \cdot \rho \cdot g) \cos \theta_i \tan \phi \, R + \sum T_j \, y_j}{\sum (A_i \cdot \rho \cdot g) \sin \theta_i \, R} \tag{2}$$

where $(A_i \cdot \rho \cdot g)$ is the weight of slice i per unit length (W_i in Fig. 1); A_i is the area of slice i; ρ is the soil density; g is the acceleration due to gravity; θ_i is the angle from horizontal to tangent at the center of slice i; R is the radius of the failure circle; ϕ is the soil friction angle; T_j is the tensile strength of reinforcement j; and y_j is the moment arm for reinforcement j.

A similar expression can be written for the factor of safety FS_m of the reinforced slope model:

$$FS_m = \frac{\sum (A_{im} \cdot \rho_m \cdot g_m) \cos \theta_i \tan \phi_m \, R_m + \sum T_{jm} \, y_{jm}}{\sum (A_{im} \cdot \rho_m \cdot g_m) \sin \theta_i \, R_m} \tag{3}$$

where the subscript m is for the model (no subscript designates the prototype). The following relationships exist between the model and prototype quantities:

$$A_{im} = (\alpha_L)^2 \cdot A_i \tag{4}$$

$$g_m = \alpha_g \cdot g \tag{5}$$

$$R_m = \alpha_L \cdot R \tag{6}$$

$$y_{jm} = \alpha_L \cdot y_j \tag{7}$$

TABLE 2—*Conventional scale factors for centrifuge modeling of static problems.*[a]

Quantity	Model Dimension / Prototype Dimension
For Static Events	
Stress, σ	1
Strain, ϵ	1
Length, L	$1/N$
Mass, m	$1/N^3$
Density, ρ	1
Force, F	$1/N^2$
Gravity, g	N
For Dynamic Events	
Time	$1/N$
Frequency	N
Acceleration	N
Strain rate	N
For Diffusion Events	
Time	$1/N^2$
Strain rate	$1/N^2$

[a]Assuming that the same soils are used in the model and the prototype.

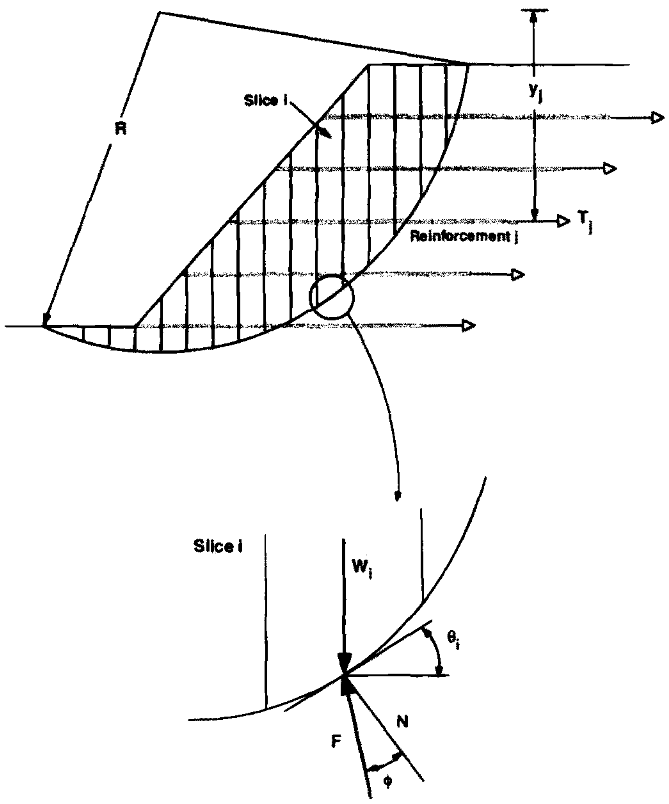

FIG. 1—*Limit equilibrium of a reinforced soil slope using a circular failure surface.*

where α_L is the scale factor for linear dimensions, and α_g is the scale factor for acceleration.

Note that a model built with a scale $\alpha_L = 1/N$ requires that the acceleration caused by gravity be scaled by $\alpha_g = N$ in order to bring the model to prototype stress levels. Incorporating Eqs 4, 5, 6, and 7 into Eq 3, the factor of safety for the model can be given as:

$$FS_m = \frac{\sum (A_i \cdot \rho_m \cdot g) \cos \theta_i \tan \phi_m R + \sum \left(\frac{T_{jm}}{(\alpha_L)^2 \alpha_g} \right) y_j}{\sum (A_i \cdot \rho_m \cdot g) \sin \theta_i R} \tag{8}$$

Since similarity between the failure responses of model and prototype requires that:

$$FS_m = FS_p \tag{9}$$

the scaling relationships for the analysis of cohesionless reinforced soil slopes can then be established by comparing Eqs 2 and 8. This comparison shows that the following similitude requirements should be satisfied:

$$\rho_m = \rho \tag{10}$$

$$\tan \phi_m = \tan \phi \tag{11}$$

$$\begin{aligned} T_{jm} &= (\alpha_L)^2 \alpha_g T_j \\ &= (1/N)^2 N T_j \\ &= (1/N) T_j \end{aligned} \tag{12}$$

Scaling requirements Eqs 10 and 11 establish that the same soil density and soil friction angle should be used in model and prototype. They can be satisfied by building the model using the same backfill soil used in the prototype structure. Equation 12 requires that the scaling factor α_T for the reinforcement tensile strength be equal to $1/N$. That is, an Nth-scale reinforced slope model should be built using planar reinforcements having $1/N$ the strength of the prototype reinforcement elements. It should be noted that the same scaling requirements would have been obtained if the radius R, instead of the vertical distance y_j, had been used as moment arm to quantify the stabilizing contribution of the reinforcements in Eqs 2 and 3.

Scaling Laws Governing Additional Aspects of the Behavior of Reinforced Slopes

Similitude requirements specific for the modeling of reinforced soil structures can be inferred from the general similitude conditions in Table 2. The similitude conditions for soil, reinforcement, and interface parameters inferred from the general conditions in Table 2 are summarized in Table 3. These scaling relations assume that the same soil is used in model and prototype and that planar inclusions are used as reinforcement elements. Note that the soil and reinforcement strength requirements are the same as those obtained in the previous section by assuming validity of limit equilibrium.

Scaling relationships for the soil shear strength and stress-strain behavior in Table 3 result directly from the scale factor of unity for stress and strain in Table 2. The scaling relationships for the planar reinforcement parameters also stem from the consideration that stresses and strains in the reinforcements should satisfy one to one scaling ($\alpha_\sigma = 1$ and $\alpha_\epsilon = 1$). However, the tensile strength in planar geosynthetic reinforcements is not defined in terms of force per unit area, σ_{ult}, but in terms of unit tension, T_{ult}, as follows:

$$T_{ult} = \sigma_{ult} \cdot t \tag{13}$$

where t is the thickness of the planar reinforcement, which is a function of the confining pressure. Considering the scaling factors for σ_{ult} and t, the scaling factor α_T for the tensile strength T_{ult} is obtained as:

$$\alpha_T = \alpha_\sigma \cdot \alpha_L = 1.1/N = 1/N \tag{14}$$

Similarly, instead of considering the conventional Young modulus E $[F/L^2]$, a stiffness parameter J $[F/L]$ is used to characterize

TABLE 3—*Scale factors for centrifuge modeling of reinforced soil structures.*

Quantity	Model Dimension / Prototype Dimension
Soil Parameters	
Shear strength parameters (c, ϕ)	1
Stress-strain behavior	1
Reinforcement Parameters	
Tensile strength (T_{ult})	$1/N^a$
Modulus (J)	$1/N^a$
Interface Properties	
Interface shear strength ($\tan \delta$)	1
Interface stress-strain behavior	1^b

[a]For the case of planar reinforcements (units for T_{ult} and J are: force/length).

[b]The scaling factor would be N if a shear stress-displacement relationship is considered to represent the actual interface behavior.

the deformability of planar reinforcements. The stiffness J is defined as:

$$J = E \cdot t \tag{15}$$

which implies the following scaling relationship:

$$\alpha_j = \alpha_\sigma \cdot \alpha_L = 1.1/N = 1/N \tag{16}$$

The constitutive behavior that a model reinforcement should have in order to satisfy the load-strain-strength scaling requirements is shown in Fig. 2. Note that, if the geotextile mechanical properties are proportional to the geotextile mass, the tensile strength and stiffness requirements of a geotextile model could be satisfied by using the same prototype geotextile material with a thickness N times smaller or, equivalently, by using the same prototype geotextile material with a mass per unit area N times smaller.

The scaling relationships governing the interface properties between soil and reinforcements are also indicated in Table 3. These relationships can also be inferred from the general scaling laws for stress and strain indicated in Table 2. Interfaces in the model and the prototype should have the same interface shear strength parameters as deduced from considering $\alpha_\sigma = 1$. However, there is controversy regarding the scaling requirements to model the stress-strain behavior of the interfaces. If the behavior of the soil reinforcement interfaces is characterized by a shear stress–shear *strain* relationship, the scale factor of unity indicated in Table 3 is inferred so that $\alpha_\sigma = 1$ and $\alpha_\epsilon = 1$ are satisfied along the interfaces. However, if the behavior of the soil reinforcement interface is characterized by a shear stress–shear *displacement* relationship (Blivet et al. 1986), the soil-reinforcement interface in the model should be stiffer (N times) than the interface in the prototype structure.

Experimental Procedures for Centrifuge Testing of Reinforced Slopes

A centrifuge study was undertaken to evaluate the performance of geotextile-reinforced slopes at failure (Zornberg et al. 1995). All reinforced slope models tested as part of this experimental testing program had the same geometry and were built within the same strong box. The models were subjected to a progressively increasing centrifugal acceleration until failure. Details of the test setup are presented in this section with the objective to carefully document the operating procedures during construction and testing of the slope models.

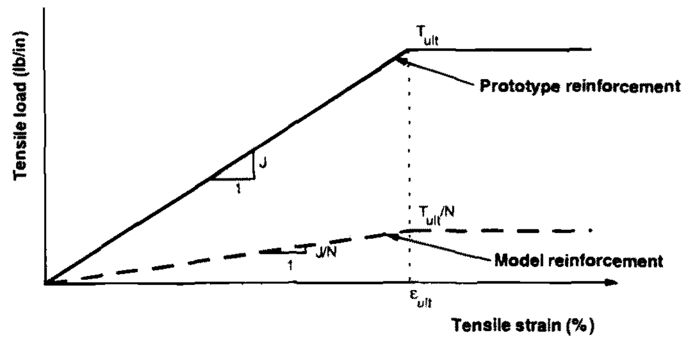

FIG. 2—*Scaling requirements between model and prototype reinforcements.*

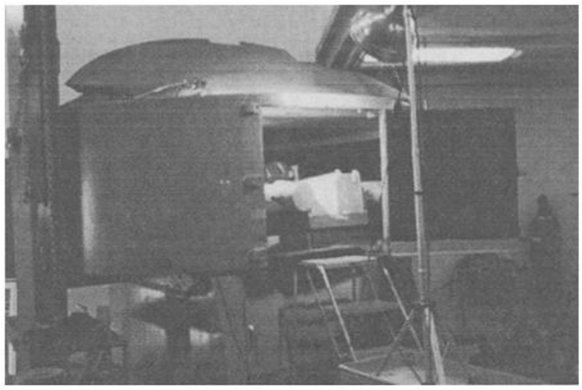

FIG. 3—*View of the Schaevitz geotechnical centrifuge.*

Geotechnical Centrifuge

The centrifuge tests were performed using the Schaevitz Type B-8-D rotary accelerator at the University of California, Davis. This centrifuge is designed to apply controlled centrifugal accelerations up to 175 g at a nominal radius of 1.0 m. The payload of the testing package can be up to 45 kg. The centrifuge, capable of reaching a maximum speed of 390 rpm, is enclosed in a protective shell. The models were placed on a swing-up bucket, so that the soil surface remains always perpendicular to the direction of the acceleration. A general view of the centrifuge is shown in Fig. 3.

Characteristics of the Reinforced Slope Models

A strong box with inside dimensions of 419 by 203 mm in plan and 300 mm in height was used to contain the model. A transparent Plexiglas plate was used on one side of the box to enable side viewing 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 was used as a reference frame for monitoring displacements within the backfill. In order to prevent scratches and to minimize side friction, a second Mylar sheet was placed over the one with a square grid pattern. A view of the strong box is shown in Fig. 4. The box was sufficiently rigid to maintain plane strain conditions in the model.

All models were built with a total height of 254 mm. The geotextile-reinforced slopes were 228.6 mm high and were built on a 25.4-mm-thick foundation layer with a facing slope inclination of 1H:2V. Air-dried Monterey No. 30 sand was used both as backfill material and foundation soil (Zornberg et al. 1995). The

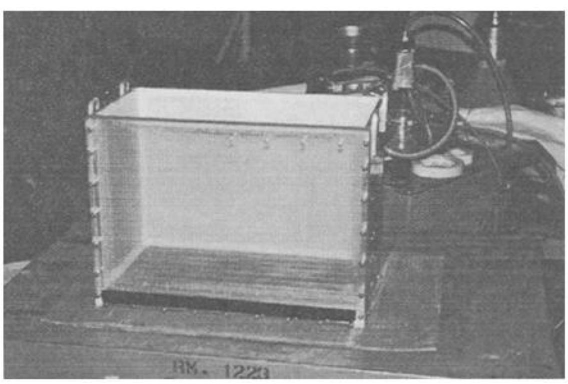

FIG. 4—*Strong box used to house the centrifuge slope models.*

overall dimensions of the geotextile-reinforced slope models are shown in Fig. 5 for the case of a model with 25.4-mm reinforcement spacing (nine reinforcement layers). The displacement transducers are also indicated in the figure.

Two types of nonwoven interfacing fabric were selected as reinforcement for the centrifuge slope models. The weaker of these geotextiles [i.e., the one with the lower ultimate tensile strength, as measured using ASTM Test Method for Tensile Properties of Geotextiles by the Wide-Width Strip Method (D 4595)] was a 100% polyester fabric with a mass per unit area of 24.5 g/m^2. The stronger of the geotextiles used in this study was a 60% polyester/40% rayon fabric with a mass per unit area of 28 g/m^2. It should be noted that prototype geotextiles with a mass per unit area almost 100 times higher than in the model geotextiles are available in the geosynthetics market. This gives an indication that models tested under accelerations as high as 100 g would still be representative of prototype structures built using available geotextile reinforcements. The number of reinforcement layers in the models varied from six to eighteen, which resulted in uniform reinforcement spacings ranging from 37.5 to 12.5 mm. All models were built using the same reinforcement length of 203 mm. The use of reasonably long reinforcement was deliberate since this study focused on the evaluation of internal stability against breakage of the geotextile reinforcements. In this way, external or compound failure surfaces were expected not to develop during testing. The geotextile layers were wrapped at the slope face of the models using typically a 50-mm-long geotextile overlap.

Construction Sequence

In order to obtain consistent soil densities and placement conditions in the reinforced soil models, carefully controlled construction procedures were used during model preparation, as follows:

- The 25.4-mm-thick sand foundation layer was placed and compacted dynamically to achieve high density in the foundation material (Fig. 6).
- The geotextile reinforcement was prepared for placement in the model (Fig. 7). Lateral flaps were used at the slope face in order to prevent lateral sloughing of the sand during testing. In order to monitor permanent deformations of the fabrics after testing, each geotextile reinforcement was marked every 12.7 mm along its centerline.
- A temporary wooden support, shaped to give a 1H:2V slope face, was placed to provide support during construction.
- The geotextile layer was aligned on the leveled backfill surface, and geotextile facing and overlap were temporarily attached to the wooden support.
- Green-colored sand was placed on the surface, along the Plexiglas wall, at the level of the reinforcement to help identify the location of the failure surface during testing. Moreover, black-colored sand markers were placed at a regular horizontal spacing (25.4 mm) in order to monitor lateral displacements on the backfill material.
- Sand was pluviated through air under controlled conditions to give uniform backfill relative densities (55 or 75%). Pluviation was performed using controlled discharge rate and discharge height in order to achieve the target density. A calibrated support and a metallic frame were used to maintain a constant height of sand discharge. Figure 8 shows the pluviation process during placement of the third sand layer for one of the models.
- Sand in excess of the target backfill level was vacuumed as shown in Fig. 9. The vacuum pressure and the height of the vacuum tube were calibrated to achieve the target height at each reinforcement level. After the target level had been achieved, a ditch was carefully vacuumed parallel to the slope face in order to embed the geotextile overlaps (see Fig. 5).
- The geotextile overlaps were detached from the wooden support, folded, and placed on the vacuumed ditch. Sand was subsequently pluviated over the geotextile overlapping length. Vacuum was used again to achieve the target backfill level at the location of the geotextile overlap. Figure 10 shows the view of one of the models after placement of the third geotextile reinforcement layer.

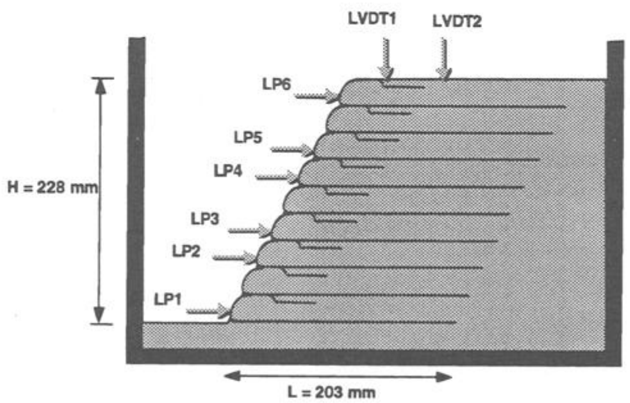

FIG. 5—*Schematic representation of a centrifuge model with 25.4-mm reinforcement spacing.*

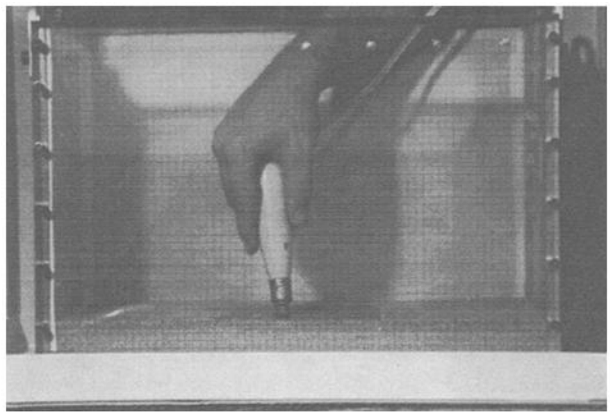

FIG. 6—*Dynamic compaction of foundation layer during construction of a reinforced slope model.*

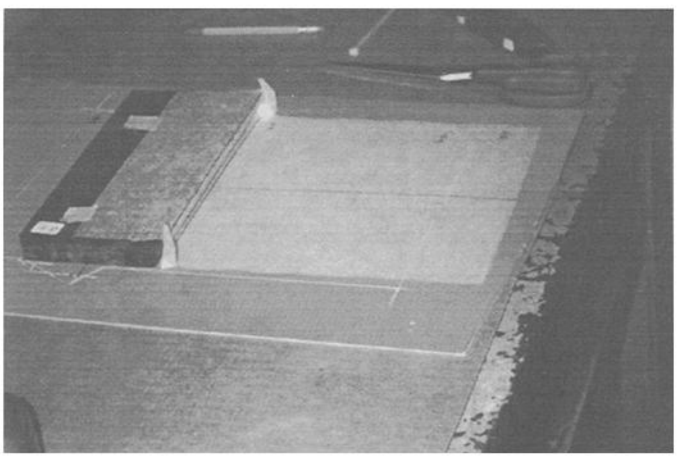

FIG. 7—*View of a geotextile reinforcement layer ready for placement.*

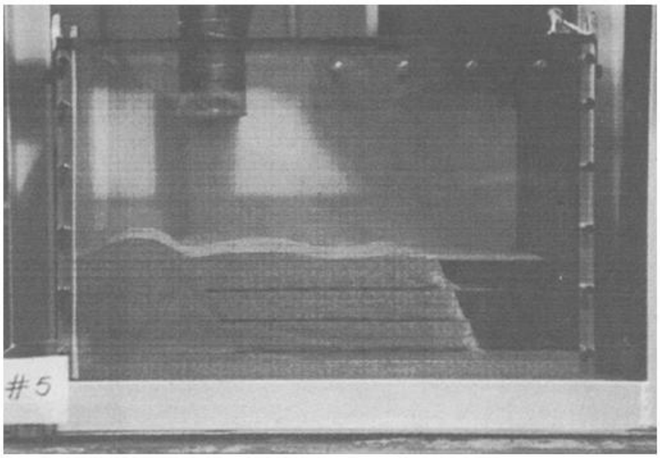

FIG. 8—*Placement of a sand layer during construction of a centrifuge model. Dry pluviation was used to achieve the target density.*

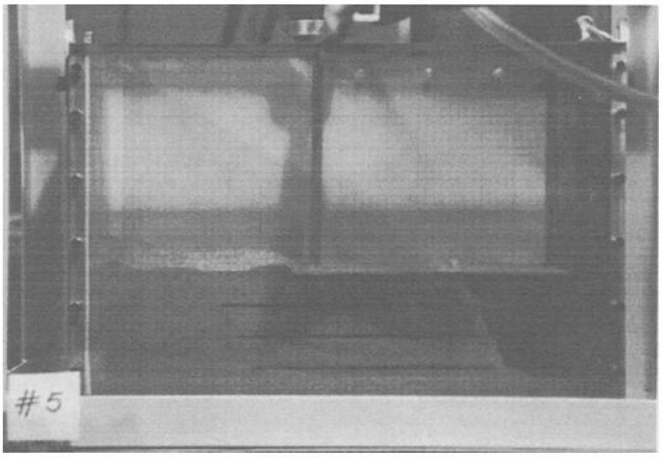

FIG. 9—*Use of vacuum to level recently pluviated sand layer.*

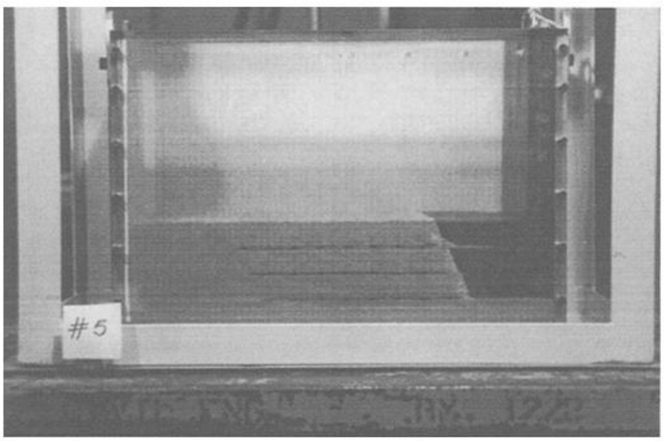

FIG. 10—*View of a model after completing placement of a sand layer. Geotextile has been wrapped around the face and the overlapping length has been embedded.*

- The next geotextile layer was placed on the leveled backfill surface, and the procedure was repeated until completion of the reinforced slope model.

Figure 11 shows the view of one of the models after construction. The wooden mold supports, which are still in place in the photo-

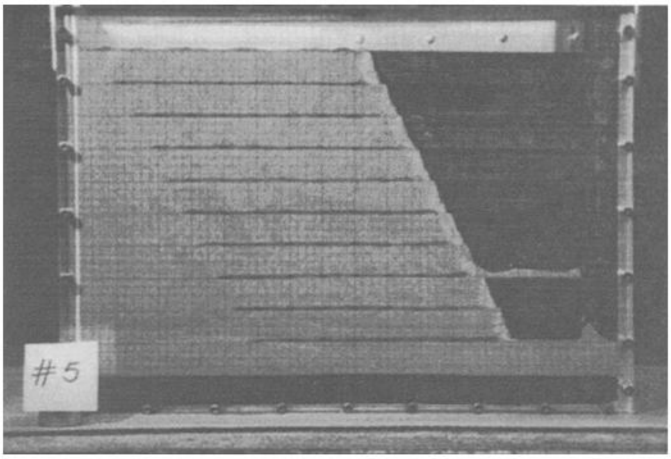

FIG. 11—*Centrifuge model, still with wooden supports in place, after completion of construction.*

graph, were removed after placement of the model in the centrifuge bucket.

Instrumentation

Sixteen electrical channels were available at the geotechnical centrifuge to monitor the behavior of the models. The signals were transmitted to the centrifuge rotor and then through a stack of slip rings to the transducers of the model in-flight.

Six linear potentiometers were used to monitor the lateral displacements at the slope face. The linear potentiometers were supported by an aluminum plate, and their elevations were adjusted in 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. Due to the small size of the reinforced model slopes, internal instrumentation was not feasible to monitor all relevant quantities at working stress levels. It was, for example, impossible to instrument the reinforcement layers for strain monitoring due to their small width and fragility.

A television camera and video recording device were used as an additional monitoring system. The television camera was mounted at the center of the rotating structure of the centrifuge. This system provided continuous monitoring of the models while testing was in progress. A 45° mirror was used to visualize 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. Figure 12 shows the centrifuge arm with the TV camera, the slant mirror, and a slope model already placed in the bucket.

Displacements in the models under increasing g-levels can be retrieved after image processing of the video records of the tests. Since the black-colored sand markers were matched during construction with the corners of the square grid on the Plexiglas side wall, their movement at increasing g-levels can be used to determine the geotextile displacements and strain distributions within the reinforced soil mass.

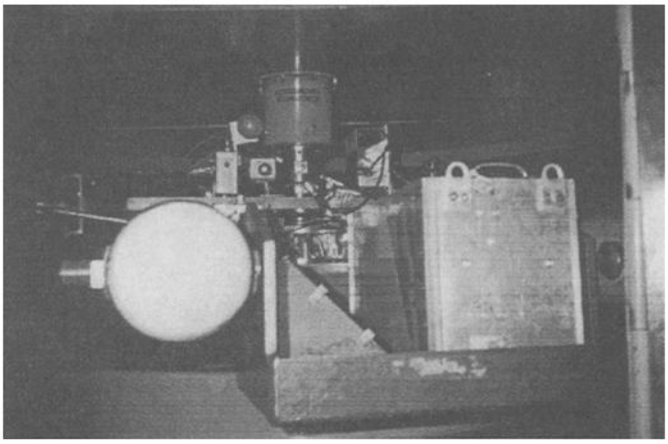

FIG. 12—*View of the TV camera and centrifuge bucket with model in place.*

Testing Procedure

After construction, the reinforced slope models were weighed and placed in the swing bucket of the centrifuge. The temporary support molds were removed, and both static and dynamic balancing of the rotating arm was performed. The slant mirror was placed adjacent to the Plexiglas wall so that the model could be observed in-flight by the closed-circuit TV camera. Figure 13 shows the top view and the image through the slant mirror of a model already placed in the swing bucket before placement of the displacement transducers. The bucket (supported by hinged pins) swings upwards during testing 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. Acceleration levels were increased by 5 *g*-level increments in the initial stages and by approximately 2 *g*-level increments in the final stages of the test. After reaching each level of acceleration, the model was held at a constant acceleration for approximately 2 min to allow equalization of the load. The black-colored sand markers were used to visualize the lateral displacements within the reinforced soil mass, and the green-colored sand was useful to visualize the failure development in the model.

After each test, the backfill was carefully vacuumed out and the geotextile reinforcements were retrieved. The tears in the retrieved geotextiles were used to identify the location of the failure surface.

FIG. 13—*Top view of a centrifuge model, already placed in the swing bucket, and of its image through the slant mirror.*

Typical Centrifuge Test Results

One of the main objectives of the centrifuge testing program was to evaluate the suitability of limit equilibrium as a basis for the design of geosynthetically-reinforced soil slopes (Zornberg et al. 1995). Consequently, all variables in the investigation were selected so that they can be taken into account within the framework of limit equilibrium. Accordingly, the selected variables were: (1) the vertical spacing of the geotextile reinforcements (four different uniform reinforcement spacings were adopted); (2) the soil shear strength parameters (the same sand at two different relative densities was used); and (3) the ultimate tensile strength of the reinforcements (two geotextiles with different ultimate tensile strength were selected).

Typical results obtained after centrifuge testing of one of the models (Model B18) are presented herein in order to illustrate the type of data obtained throughout the study. Interpretation of the failure mechanisms and implication of the results on the design of geosynthetically reinforced slopes are beyond the scope of this paper and will be presented in subsequent publications.

The history of centrifugal acceleration during centrifuge testing of Model B18 is indicated in Fig. 14. 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. Failure development in the reinforced slope could be identified from the TV images. However, the settlement at the crest of the slope monitored by LVDTs more accurately identified the moment of failure. 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 15 shows the failure surface that developed in Model B18, as observed after unloading the model from the centrifuge bucket. The failure surface is clearly defined and goes through the toe of the reinforced slope.

Following the experiment, the model was carefully disassembled in order to examine the tears in the geotextile layers. Figure 16 shows one of the geotextile layers retrieved from Model B18 (fourth reinforcement layer from the base of the slope). Since this layer was located towards the base of the slope, the failure surface intersected both the primary reinforcement layer and the overlapping length. The retrieved geotextiles showed clear breaks at the location of the failure surface, which indicates that internal failure occurred when the reinforcements achieved their ultimate tensile strength. The geotextile overlaps of the layers located towards the base of the slope model also showed clear breaks, which indicates that the overlaps also contributed to the stability of the slope. No

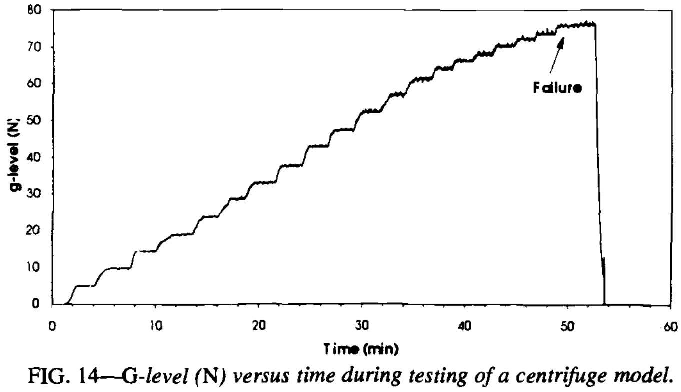

FIG. 14—*G-level* (N) *versus time during testing of a centrifuge model.*

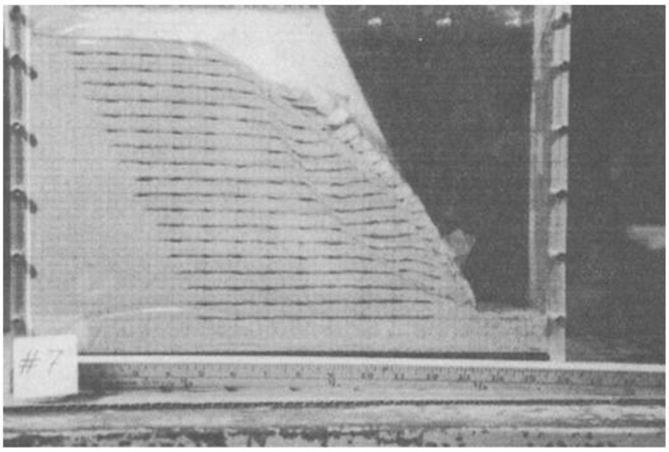

FIG. 15—*View of the failure surface obtained in a centrifuge model after testing.*

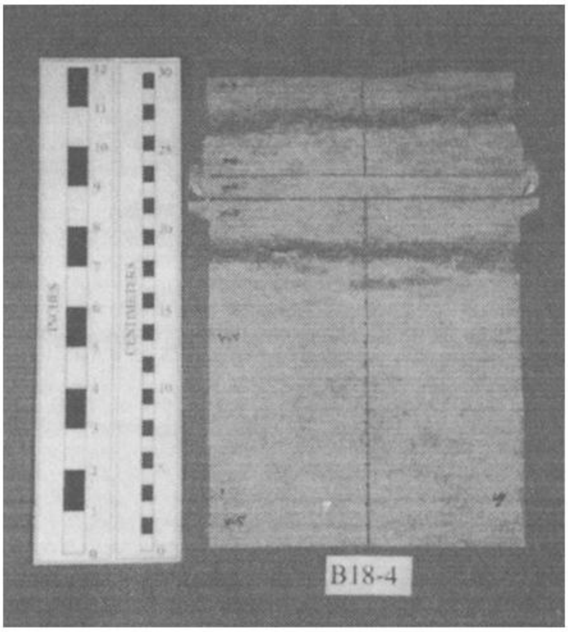

FIG. 16—*Geotextile layer retrieved from a centrifuge model, showing tensile tears on both the primary reinforcement and the overlapping length.*

evidence of pullout was observed, even on the short overlapping layers. The shape of the geotextile tears would have been curved if significant boundary effects had occurred due to side friction. However, the tears in the geotextile were perpendicular to the direction of loading, which indicated no evidence of lateral friction between the model and the walls of the centrifuge box.

In-flight visual monitoring of the models through the Plexiglas wall and post-failure evaluation of the retrieved geotextiles proved invaluable in the interpretation of the results of the testing program described herein. In fact, the necessary basis for determination of the forces acting on the reinforced slope at failure was provided by visual monitoring of the performance of the models, which included the assessment of the shape of the failure surfaces, the identification of the failure mechanisms, and the verification that the boundary effects due to lateral friction were negligible.

Conclusions

The purpose of this paper was to present: (1) a state-of-the-art review on the centrifuge modeling of reinforced soil structures; (2) a derivation of the conditions of similarity specific for the problem under study; and (3) a description of the experimental testing procedures implemented in a recent centrifuge study, undertaken to evaluate the performance of geotextile-reinforced slopes at failure.

Two main observations could be drawn from the state-of-the-art review of centrifuge studies that evaluated the performance of reinforced soil structures: (1) the majority of previous investigations focused on the performance of reinforced soil vertical walls; and (2) limit equilibrium approaches (used in the design of reinforced soil slopes) have rarely been used to predict the failure of centrifuge models.

Scaling laws governing the behavior of cohesionless reinforced soil slopes at failure were derived by assuming the validity of limit equilibrium. The same soil density and soil friction angle should be used in model and prototype in order to satisfy similitude requirements. Moreover, it was shown that Nth-scale reinforced slope models should be built using planar reinforcements having $1/N$ the strength of prototype reinforcements in order to obtain the same stability factors of safety in model and prototype structures.

Finally, the experimental testing setup and procedures used during a recent centrifuge testing program (including the construction, testing, and monitoring of the centrifuge models) were documented in detail. The carefully controlled construction procedures followed during model preparation were essential to guarantee consistent backfill densities and placement conditions and to produce consistent model behavior. As designed, internal failure occurred in all tests. Detailed interpretation of the experimental results is given elsewhere (Zornberg et al. 1995) and will be described further in subsequent publications. Nevertheless, typical results obtained from one of the models were presented. Visual monitoring of the models during centrifuge testing and evaluation of the geotextile reinforcements retrieved after failure proved invaluable in the interpretation of the test results. The breakage pattern observed in the retrieved geotextiles indicated that internal failure occurred by breakage of the reinforcements without evidences of pullout. Moreover, the tears in the geotextiles indicated that boundary effects due to lateral friction between the model and the centrifuge box were negligible. These results suggest that centrifuge model testing is a useful tool to investigate the performance of reinforced soil structures at failure, particularly in the absence of prototype failure records.

Acknowledgments

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