Application of Centrifuge in Modeling Geosynthetically Reinforced Systems

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ABSTRACT: There is a growing community of researchers that uses the geotechnical centrifuge, as a research tool, to gain insight into the mechanistic behavior of geosynthetically reinforced earth retaining structures. In this paper the principles of stress-correct physical modeling are highlighted. Examples of several case histories are provided to show how researchers in different countries of the world have used this modeling technique in their work. The preliminary results of an ongoing research project on geotextile reinforced cohesive soil slopes and embankments using geotechnical centrifuge are presented.

1 INTRODUCTION

In the last two decades the demand to use cost-effective geosynthetic materials for various applications in the construction industry has increased dramatically. This trend is reflected by the rise of geosynthetic manufacturing throughout the world, and the parallel increase in the number of conference sessions, journal papers, and dissertation topics associated with geosynthetic material in both developed and developing countries. New engineering applications are often proceeded by research using one or both of physical and numerical modeling. The centrifuge modeling technique is one powerful tool being used increasingly by geotechnical engineers over the last two decades, but has a history of use for some 70 years in the former Soviet Union, to solve various complex engineering problems by means of stress-correct physical models. The purpose of this paper is to introduce the concept of centrifuge modeling, particularly to those not familiar with the technique in the geosynthetic research community. Examples of several case histories are provided to show how investigators in different countries of the world have used this technique in their research work. The preliminary results of a research project in progress examining the behavior of geotextile reinforced cohesive earth retaining walls, slopes, and embankments using geotechnical centrifuge is presented.

2 PRINCIPLES OF CENTRIFUGE MODELING

In many geotechnical problems the self-weight of the soil, increasing substantially with depth, creates the stress gradient that dominates soil deformations, and in many cases leads to failure of the soil, and of the structures resting in, on, or under the soil. If model testing is to be done using real soil, then to ensure similarity between the response in a model and the response in the corresponding full-scale case, stresses must be similar at geometrically corresponding points to ensure that strain will be also. This means that the self-weight stress gradient in the full-scale situation, must be replicated in the model. This can be achieved by spinning a model of scale 1:N around on a centrifuge to effect an acceleration of N times gravity.

The concept of centrifuge modeling is illustrated in Figure 1 in the context of modeling a slope stability problem. Self-weight normal vertical stresses at the base of the slope, well back from the slope itself, will equal γH due to soil overburden (see part "c" in Figure 1). In a 1-g model, say 20 times smaller but geometrically identical, built of the same soil, self-weight normal vertical stresses will be 1/20th that in the full-scale, as shown in part "a" of Figure 1. If, however, the soil in the same model were made to weigh 20 times its self-weight at 1-g, by spinning the model around on the centrifuge to create an outward acceleration of N=20g, self-weight normal vertical stresses at the base of the model will again become equal

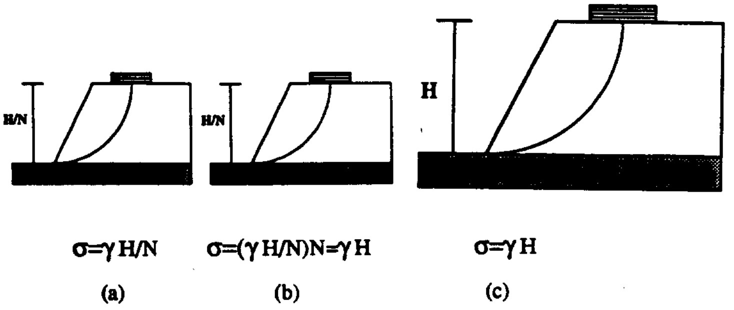

Figure 1 Basic concept of stress-correct physical modeling. (a) 1-g model; (b) N-g model (centrifuge model); (c) full-scale prototype.

to those in the full scale prototype, and correspond also at all intermediate geometrically similar points. If boundary conditions and stress histories correspond in model and full-scale, then the response in the model should be equal to the response in the full-scale prototype, consistent with the scaling relationships in Table 1 governing modeling of different geotechnical parameters.

Model laws that govern a phenomena in question must be derived from dimensional analysis to relate model behavior to the behavior of full-scale events. Based on dimensional analysis the similarity in behavior between small-scale model and a prototype is attained when all parameters which influence the behavior of a physical system, arranged in so-called dimensionless ratios or Buckingham π-products, have the same values in both the model and the corresponding prototype. There are situations where perfect similarity can not be achieved in the centrifuge models. A number of centrifuge modelers have discussed these limitations in detail (see, for example, Scott and Morgan, 1977; Schofield, 1980; and Fuglsang and Ovesen, 1988) and it is correct that any dissimilarities be examined to determine that their influences on model behavior are either insignificant or quantifiable before extrapolation to full-scale is warranted. Still, while compromises may be required, it is also the way with numerical techniques and even more so with 1-g models not at full-scale. For this reason the various research techniques are excellent compliments to each other when used properly.

Table 1 Scaling factors in centrifuge modeling technique (Fuglsang and Ovesen, 1988).

	parameter	symbol	dim. less number	similarity requirement	scaling factor
1	acceleration	a		$N_a =$	n
2	model length	l		$N_l =$	$\frac{1}{n}$
3	soil density	ρ		$N_\rho =$	1
4	particle size	d	$\frac{d}{l}$	$N_d =$	1
5	void ratio	e	e	$N_e =$	1
6	saturation	S_r	S_r	$N_S =$	1
7	liquid density	ρ_l	$\frac{\rho_l}{\rho}$	$N_{\rho l} = N_\rho =$	1
8a	surface tension	σ_l	$\frac{\sigma_l}{\rho_l a d l}$	$N_\sigma = N_\rho N_a N_d N_l =$	1
8b	capillarity	h_c	$\frac{h_c \rho_l a d}{\sigma_l}$	$N_h = N_\sigma N_\rho^{-1} N_a^{-1} N_d^{-1} =$	$\frac{1}{n}$
9a	viscosity	η	$\frac{\eta}{\rho_l d \sqrt{al}}$	$N_\eta = N_\rho N_d N_a^{\frac{1}{2}} N_l^{\frac{1}{2}} =$	1
9b	permeability	k	$\frac{k\eta}{d^2 \rho_l a}$	$N_k = N_d^2 N_\rho N_a N_\eta^{-1} =$	n
10	particle friction	φ	φ	$N_\varphi =$	1
11	particle strength	σ_c	$\frac{\sigma_c}{\rho a l}$	$N_\sigma = N_\rho N_a N_l =$	1
12	cohesion	c	$\frac{c}{\rho a l}$	$N_c = N_\rho N_a N_l =$	1
13	compressibility	E	$\frac{E}{\rho a l}$	$N_E = N_\rho N_a N_l =$	1
	time:				
14	inertia	t_1	$t\sqrt{\frac{a}{l}}$	$N_t = N_l^{\frac{1}{2}} N_a^{-\frac{1}{2}} =$	$\frac{1}{n}$
15	lam. flow	t_2	$t\frac{k}{l}$	$N_t = N_l N_k^{-1} =$	$\frac{1}{n^2}$
16	creep	t_3			1

3 CASE HISTORIES

Several researchers in various parts of the world have used the centrifuge to study the behavior of geosynthetically reinforced soil retaining structures. They used different simulant materials to model the geosynthetic reinforcing elements in their small-scale models. According to dimensional analysis the geosynthetic simulant used as reinforcement should be N times weaker than the full-scale geotextile, where N is at once the scale and the gravitational acceleration of the model. This is because while stresses in models are equal to those at full-scale, the reduction in dimensions means that forces are N times less in a model than in a prototype. Table 2 is a list of six case histories involving centrifuge modeling of geotextile reinforced soil retaining structures. This list does not include the work of other researchers who used centrifuge technique to study "strip" reinforced soil retaining walls which are not included in this paper. The cross-sections of the various small-scale models for different case histories are illustrated in Figure 2.

4 RESEARCH ON GEOTEXTILE REINFORCED CLAY SLOPES

Ongoing research by Porbaha and Goodings at the University of Maryland at College Park is to examine the behavior of geotextile reinforced cohesive soil retaining systems using the geotechnical centrifuge. In this study, models are 152 mm high, and consist of eight layers of equally-spaced interfacing fabric used as the reinforcement

Table 2 Case histories in centrifuge modeling of geosynthetically reinforced earth retaining structures

CASE	CONFIGURATION OF SMALL SCALE MODEL	REINFORCING ELEMENT (GEOSYNTHETIC SIMULANT)	CENTRIFUGE FACILITIES	INVESTIGATOR	COUNTRY
I	40 mm high 3 to 4 layers of reinforcement backfill: Danish Normalsand	Chlorin-treated gauze (T=0.18 to 3.26 kN/m)	Danish Engineering Academy	Ovesen (1984)	Denmark
II (a)	152 mm high 8 layers of reinforcement backfill: Fontainebleau sand	Non-woven fabric (T=0.066 kN/m) Plastic netting (T=0.53 kN/m)	University of California at Davis	Mitchell et al. (1988)	U.S.A.
II (b)	508 mm high 8 layers of reinforcement backfill: gravelly sand	Non-woven geotextile (needle-punched) (T=44 kN/m)	National Geotechnical Centrifuge (U.C., Davis)	Jaber et al. (1990)	U.S.A.
III	600 mm high 6 layers of reinforcement backfill: sand or clay	Non-woven geotextile heat-bonded needle punched (T=7.2 kN/m)	Laboratoire Central des Ponts et Chaussees (LCPC, Paris)	Matichard et al. (1988)	France
IV	114 to 228 mm high 4 to 20 layers of reinforcement backfill: Kaolin clay	Interfacing fabric (Interlon) (T=0.701 kN/m)	University of Maryland, College Park	Alvarez (1988) Suah (1989)	U.S.A.
V	100 mm high 4 layers of reinforcement backfill: Toyoura sand	Non-woven fabric (T=0.285 kN/m)	Public Works Research Institutes, Tsukuba	Taniguchi et al. (1988)	Japan
VI	variable height 1 layer of reinforcement backfill: sand	Non-woven fabric (polyester) (T=0.72 kN/m)	Port & Harbor Research Institute, Yokosuka	Terashi et al. (1988)	Japan

T= Tensile strength of reinforcement simulant

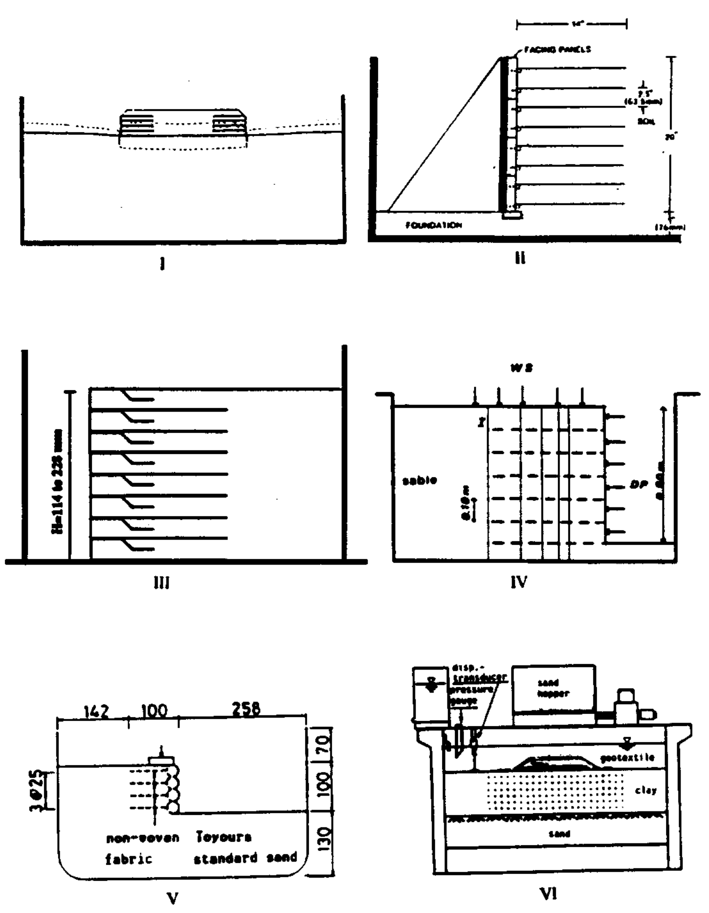

Figure 2 Cross-sections of reduced-scale models based on the case histories in table 2.

simulant, backfilled with kaolin clay. The models, tested to failure on the centrifuge, are being developed to study the influence of foundation type (weak, firm, and rigid); slope batter angles; the geometry of reinforcement; and the length of reinforcement. Finally, lime is being added to the kaolin backfill in some models to examine the effect on wall stability due to the resulting improvement in soil strength. Porbaha and Goodings (1994) reported on a set of models which examined the behavior of geotextile reinforced models on weak foundations. Models reinforced with constant, or variable length of reinforcement with depth, failed in combined mechanisms of base failure and rotational sliding. The bottom layer of reinforced soil underwent differential compression and as a result failure involved a marked flattening of the original profile, as shown in Figure 3. Deformation and failure were accompanied by geotextile rupture or strain, but there was no evidence of pullout. A trial full-scale wall is also planned for comparison to the behavior of small-scale models.

5 SUMMARY

Stress correct physical centrifuge modeling of geosynthetically reinforced soil structures is receiving

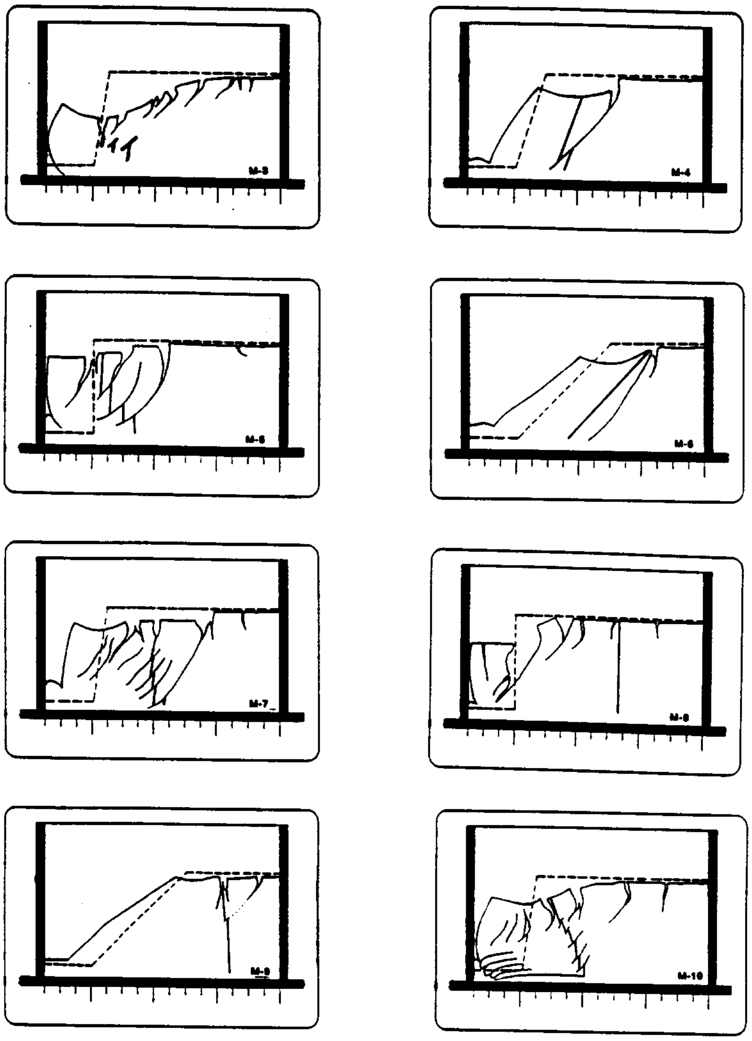

Figure 3 Profiles of models on weak foundations after failure in the centrifuge.

more attention from the geosynthetic research community because of its ability to provide dramatic insight into the failure mechanisms and prefailure behavior. The concept of centrifuge modeling, and several international case histories are discussed to show how investigators have used the geotechnical centrifuge to study the behavior of geosynthetically reinforced soil structures. The preliminary results of a research project in progress on centrifuge modeling of geotextile reinforced cohesive slopes are presented.

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