REINFORCED EARTH AND ADJACENT SOILS: CENTRIFUGE MODELING STUDY

By D. J. Goodings[1] and J. C. Santamarina,[2]
Associate Members, ASCE

INTRODUCTION

The excellent behavior of reinforced soil retaining walls under a wide range of site conditions has given designers using conventional design assumptions little cause for concern regarding the effects of either the foundation soil or the retained fill supported by the wall [Fig. 1(*a*)]. In the meantime, analytical and 1-g experimental studies on the effect of foundation conditions on wall behavior have produced contradictory conclusions. This research examined experimentally the effect of foundation soil and retained fill on wall behavior. The primary technique used in the study was centrifuge modeling, first applied to reinforced soil walls by Bolton et al. (1978).

Preliminary Studies—Description

Dimensional analysis included variables representing the characteristics of the system such as the reinforcing strips, the backfill, the foundation, the retained fill, and the gravitational or centrifugal acceleration. Dimensionless π groups not equal in model and prototype were assessed for scale effects, in either 1-g laboratory models or centrifuge parametric studies, or both. Those dissimilar π groups included w/d, $\delta h/\delta v$, $\delta v/H$, $tw/(\delta h \cdot \delta v)$, where w is the reinforcing strip width, d is the grain diameter, δh and δv are the horizontal and vertical spacings of the strips, H is the wall height, and t is the reinforcing strip thickness.

Even though the models were designed to observe failure by strip breakage rather than pullout, the effect of w/d on soil-strip friction was studied experimentally at 1 g. The conclusion was that soil strip friction reaches the maximum value when w/d is about 30 or greater for both peak and residual conditions [see also Bacot et al. (1978), Schlosser and Elias (1978), and Santamarina (1984)]. The effects of variation in the π groups $\delta h/\delta v$, $\delta v/H$ and $tw/(\delta h \cdot \delta v)$ are considered in this paper.

Properties of the materials used in the models are summarized in Table 1. The choice of aluminum foil for the reinforcing strips and the skin was based on a compromise between similarity requirements and constructability, and was consistent with the precedent of previous researchers [for example, Bolton and Pang (1982), and Smith and Wroth (1978)].

The models were constructed in two phases. First, the strips-skin assembly was prepared using a technique outlined in Santamarina (1984). Then, a

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[1] Assoc. Prof., Dept. of Civ. Engrg., Univ. of Maryland, College Park, MD 20742.

[2] Asst. Prof., Dept. of Civ. and Envir. Engrg., Polytechnic Univ., 333 Jay Street, Brooklyn, NY 11201; formerly, Grad. student, Univ. of Maryland, College Park MD.

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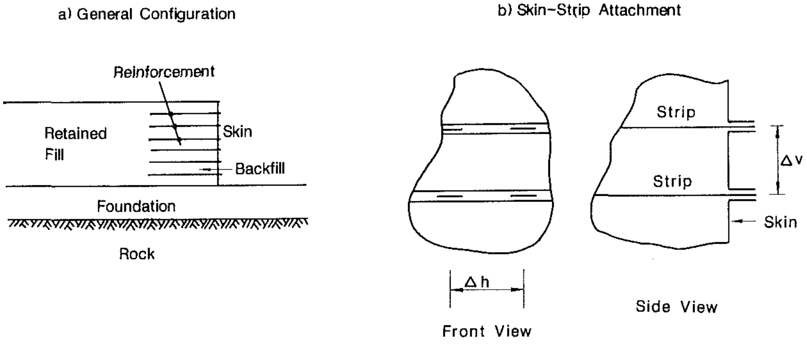

FIG. 1. Reinforced Soil Retaining Wall Configuration

temporary support was positioned on top of the model foundation, against which the strips-skin assembly was steadied during construction. The wall was constructed by lowering a row of strips into the horizontal position, raining sand onto that row until the next row of strips was reached, and then

TABLE 1. Model Material Properties

Material property (1)	Value (2)
(*a*) Ottawa Sand	
D_{50}	0.4 mm
C_u	1.43
$\gamma_{\max}$	17.26 kN/m^3
$\gamma_{\min}$	14.82 kN/m^3
G_s	2.65
γ	17.0 kN/m^3[a]
(*b*) EPK Kaolin	
D_{90}	0.01 mm
D_{50}	0.001 mm
Liquid limit	47
Plastic limit	26
Activity	0.35
G_s	2.63
Foundation	Mixed at w = 72% Consolidated to 270 kN/m^2
Retained fill	Slurry, w = 72% γ = 15.3 kN/m^3
(*c*) Aluminum Foil (Alloy 8111)[b]	
Tensile strength	86,300 kN/m^2
Thickness	24 μm
Elongation	6.9%

[a] Placed by pluviation from 0.4 m.

[b] H. H. Buck, Reynolds Metal Company, 1984.

repeating the process. The retained fill was built up at the same time.

The test procedure involved slowly increasing acceleration on a 1.2-m-radius 10-g-ton Genisco centrifuge, until catastrophic failure of the retaining wall occurred at N_f gravities. The aluminum foil skin furnished an excellent record of the position of the initiation of failure, and the broken strips indicated the pattern of propagation of failure.

MODEL TESTING AND RESULTS

Two series of models were tested. The geometry of the tall models ($L/H = 0.76$) was similar to that of prototype walls; short models ($L/H = 1.36$) were tested to examine the behavior of wider walls. Model characteristics are summarized in Table 2, which also presents model test results in terms of the type of foundation and retained fill, and a dimensionless ratio ψ. This ψ was adopted as an index of wall safety against strip breakage, and it is defined as $\psi = (N_f \gamma H K_a \delta v \delta h)/F$, where F is the tensile strength of a strip in units of force, N_f is the centrifugal acceleration at failure in multiples of Earth's gravity, γ is the unit weight of the backfill, and K_a is the active earth pressure coefficient for the backfill, defined as $K_a = \tan^2[45° - (\phi/2)]$. If $\psi = 1.0$ when a wall collapses due to strip breakage, then it is an accurate portrayal of the forces in the wall; if ψ is greater than one, then the forces

TABLE 2. Tall and Short Model Data

Foundation (1)	Retained Fill[a]		
	Aluminum (2)	Sand (3)	Slurry (4)
(a) Tall Models: $L/H = 0.76$; $H = 144$ mm; $\delta v = 16$ mm; $\delta h = 30$ mm; and $w = 8$ mm			
Aluminum	1.468 (1)	1.483 (1)	1.366 (2)
Sand 25 mm	1.448 (1)	1.359 (5)	1.287 (1)
Clay 25 mm	1.874 (2)[b]	1.858 (1)	1.703 (1)
Additional:			
Sand 50 mm	1.496 (1)	—	—
Sand 75 mm	—	1.391 (1)	—
(b) Short Models: $L/H = 1.36$; $H = 80$ mm; $\delta v = 16$ mm; $\delta h = 50$ mm; and $w = 8$ mm			
Aluminum	1.196 (2)	1.378 (2)	1.066 (2)
Sand 25 mm	1.152 (2)	1.341 (1)	1.112 (1)
Clay 25 mm	>1.678 (2)[c]	—	—
Additional:			
Aluminum	1.305 (1)[d]	—	1.190 (1)[e]
Sand 50 mm	1.200 (1)	—	—
Sand 75 mm	—	1.324 (1)	—

[a] Numbers are average ψ values (the number of tests run is shown in parentheses).
[b] One model did not fail at $\psi \leq 1.915$.
[c] Neither of the two models failed.
[d] Friction reducing layer applied to aluminum backfill.
[e] Light weight slurry: $\gamma = 10.3$ kN/m^3.

causing failure are less than those considered, and a design based on ψ would be conservative.

Stability of Tall Models

The pattern of behavior in Table 2(*a*) indicates that the effect of major changes in backfill on wall stability is minor, and much lower than calculations based on the aforementioned assumptions would predict. While there are no data to assess separately the effect of the shear and normal forces on the back of the wall, the difference in ψ between the walls with aluminum and sand retained fill points to the influence of shear on the stability of the wall.

The influence of foundation type on retaining wall behavior has been unclear to researchers because it has appeared to be very small. Smith and Wroth (1978) found no systematic effects in their 1-g models and both Naylor (1978), and Jones and Edwards (1980) concluded from analytical modeling that the influence was small. Data in Table 2(*a*) contradicts their conclusion. For models with a given backfill, ψ, which does not consider foundation conditions, differed between 28% and 32%, depending on the stiffness of the foundation soil; model walls on clay foundations consistently performed better than those on aluminum and sand foundations. This indicates that a beneficial effect should be expected for walls on soft foundations (i.e., when settlements preceding failure are in the order of 1% of the wall height). The effect on ψ of changing the depth of the sand foundation from $D/H = 0.25$ to 0.75 was minor (in this case, the settlement of the foundation can be estimated to be in the order of one thousandth the wall height).

The low sensitivity of wall performance to different backfills and the beneficial effect of soft foundations on wall strength emphasize the flexible nature of reinforced soil walls with a typical L/H ratio: they are capable of advantageously redistributing internal stresses, rather than acting as rigid bodies. These trends and the fact that ψ in all cases was significantly greater than one indicate that the design assumptions are quite conservative.

Stability of Short Models

The data for short models (with a higher than typical L/H ratio) shown in Table 2(*a*) confirm in general the trends observed with tall models, but the sensitivity of the wall to changes in retained fill increased, contrary to expectations. In addition, values of ψ at failure are lower than for tall models with similar adjacent soils, indicating a less stable condition.

This behavior may be attributed in large part to differences in strip geometry measured by the $\delta h/H$ and $\delta v/H$ ratios; they reflect the capacity for cooperation between neighboring strips to reinforce the soil retaining wall. In prototypes, values of $\delta h/H$ and $\delta v/H$ are smaller than in the short models, taking best advantage of this cooperative effect. In addition, the model aluminum reinforcement undergoes less elongation before failure (6.9%), and permits less redistribution of stresses than the steel reinforcing used in the field (15% elongation at failure).

Significant difference between the behavior of short walls with aluminum and sand retained fills is apparent from Table 2(*b*). To study whether this was an effect of the shear force at the vertical boundary between the backfill and the retained fill, two identical model walls were tested with untreated aluminum retained fill and compared in behavior to a third model wall, with aluminum retained fill treated with a friction reducing system to decrease the upward drag on the back of the reinforced soil wall as it settled (Santamarina and Goodings 1988). The result showed an improvement in wall stability of 9%, as measured by ψ.

Three foundation soils were included in the series of short models. The superiority of wall stability on soft foundations observed in the tall models was even greater in the short models. The effect on ψ of changing the depth of the sand foundation was again minor in short models.

CONCLUSIONS

Reinforced soil retaining wall models were tested in a geotechnical centrifuge to study the effect of the retained fill and the foundation on the performance of walls. For tall models with L/H equal to 0.76, which is similar to prototype walls, the effect of the retained fill on the overall internal stability of the wall was found to be small. Short models, with L/H equal to 1.36, were more sensitive to changes in retained fill, possibly due to a distribution of reinforcing strips that did not lead to efficient reinforcing of the soil. The influence of vertical shear from the retained fill acting on the back of the wall was highlighted. In both tall and short models, the foundation was found to have greater effect than typically assumed, and soft foundations led to superior wall performance.

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