Cautions of Reinforced Earth with Residual Soils

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For many years Reinforced Earth has been an alternative to the conventional retaining system. Experience has been gained in many soil types across the United States. The result has been the development of reinforced earth backfill specifications that provide for granular backfill properties in most soils. The performance and problems of a project that uses fine-grained residual soils as Reinforced Earth backfill are documented in this paper. Fines and moisture content caused strength reductions, which resulted in wall deformations. A thorough investigation was conducted, including extensive laboratory testing. Test results demonstrate the reduction in strength with increased fines and water content. The design strip pull-out capacities in fine-grained residual soils and coarse-grained highly micaceous soils are sensitive to variations in the amount of fines and water content. Strict quality control is necessary during construction of any earth structure in these soils.

Construction of a Reinforced Earth wall began during the winter of 1978-1979 in Virginia. The wall consisted of nine sections, which totaled more than 35,000 ft^2 of exposed surface area. The walls varied in height; the maximum section was approximately 23 ft. A simplified location plan is shown in Figure 1. Many similar walls have been designed and constructed in Virginia by the Reinforced Earth Company; however, the problems that evolved on this job provide a valuable lesson for future construction in residual soils.

The project site is located in the Piedmont geologic province. On-site soils are residual fine sandy micaceous low-plasticity silts. These soils, although often suitable for use as structural fill, were not considered suitable Reinforced Earth backfill. The job specifications required that the Reinforced Earth backfill be nonplastic and less than 15 percent pass the No. 200 sieve. The gradation requirements were as follows:

Sieve Size	Percentage Passing
No. 200	0-15
3 in.	75-100
6 in.	100

This was a standard requirement for Reinforced Earth walls constructed at that time. Research has shown that nonplastic soils that have less than 15 percent fines derive their internal strength from intergranular friction (1).

A compaction moisture content within ±2 percent of optimum with a minimum density greater than 95 percent of standard Proctor maximum dry density was also specified. For a truly granular fill this criteria are not as critical as others. Compaction moisture content significantly affects undrained strength of clayey or silty soils. However, the internal friction of a granular soil is only moderately reduced with increased compaction, moisture content, or saturation (2,3).

DESIGN

The wall facings were precast reinforced concrete. Typically, four Reinforced Earth strips were attached to each panel on approximately 2.5-ft spacings. The strips were ribbed galvanized steel 1.6x 0.2 in. in dimension. The strips varied in length relative to their position in the wall from 14 ft to approximately 20 ft.

The subsurface investigation performed for this project revealed no permanent groundwater table within the project grading limits. The Reinforced Earth granular backfills were expected to provide

sufficient drainage of transient groundwater behind the wall. Therefore, no subsurface drainage system was installed.

During the design phase the Reinforced Earth Company had conducted laboratory strip pull-out capacity tests and strength tests on coarse-grained soils from local borrow sources. This information, in combination with much field testing in a variety of soil types, provided the basis for designing the wall. The backfill selected by the contractor was a residual gravelly, silty sand to be trucked in from off-site. Initial sampling of the borrow source indicated that it would meet the criteria specified for grain size.

The reinforcing strips were designed for strip pull-out capacity based on data obtained from samples that met the gradation specifications. The design pull-out capacity is dependent on length, position in the wall, and overburden pressure. The internal wall design allowed for a safety factor of at least two against strip pullout. The ultimate strip pull-out capacity allowed for a small safety margin in the event that hydrostatic pressures were applied to the wall from a transient groundwater condition.

PROJECT HISTORY

The sequence of events related to the displacements and reconstruction of the wall are summarized in Figure 2. Construction of the wall began in October 1978. The walls were nearly completed by December of that year. Some construction continued during the winter; however, earthwork was halted due to adverse weather conditions. In February 1979 an early thaw was preceded by several days of above normal precipitation (Figure 2). This amounted to approximately 22 in. of accumulated snowfall that melted over a 7-day period. During this time movements were noted along some sections of the Reinforced Earth walls. Typical movements consisted of tilting 10 to 12 in. out of plumb at its maximum section, which caused the wall facing to apply a lateral force on some adjacent piers. An example of the magnitude of movement is shown in Figure 3.

A detailed investigation was subsequently conducted into the probable cause of the movements. Recommendations were given concerning remedial construction of walls after the investigation was completed. The damaged panels were removed along with the Reinforced Earth backfill. New backfill was placed and the walls were reconstructed by December 1979. The reconstructed wall has experienced no problems in 3 years of service.

INVESTIGATIVE FINDINGS

The investigation consisted of 10 test borings and four hand-dug excavations along the wall (see Figure 1). All test holes were located 8 ft behind the face of the Reinforced Earth walls.

Three types of sampling procedures were used during the investigation to determine whether the method of sampling altered the grain size distribution of the samples obtained. Sampling at test holes TH-1-10 was performed with a 3-in. diameter hollow stem auger that had 1-7/8-in. wide spiral flights. All samples obtained were auger cuttings except for three undisturbed 3-in.-diameter Shelby
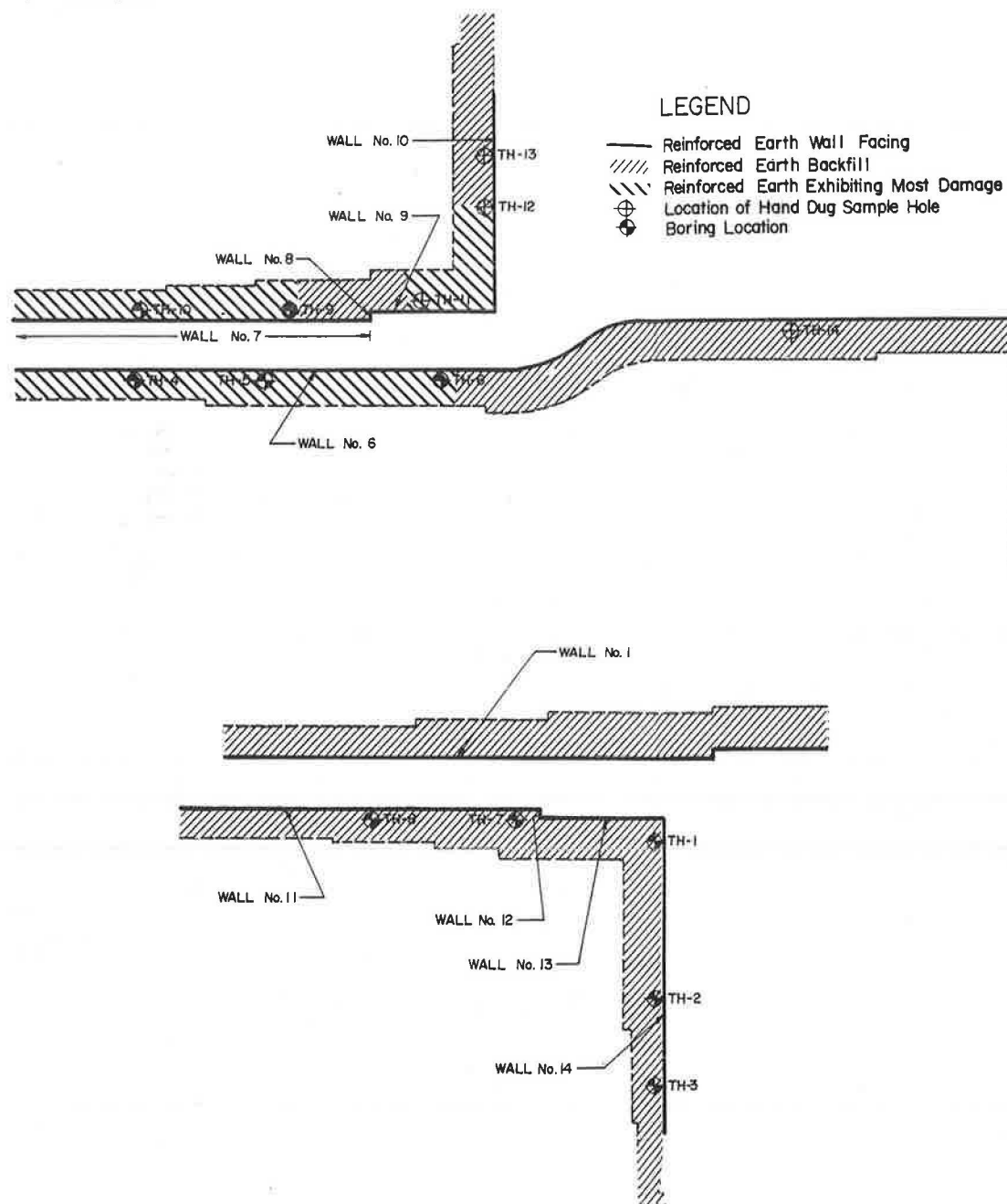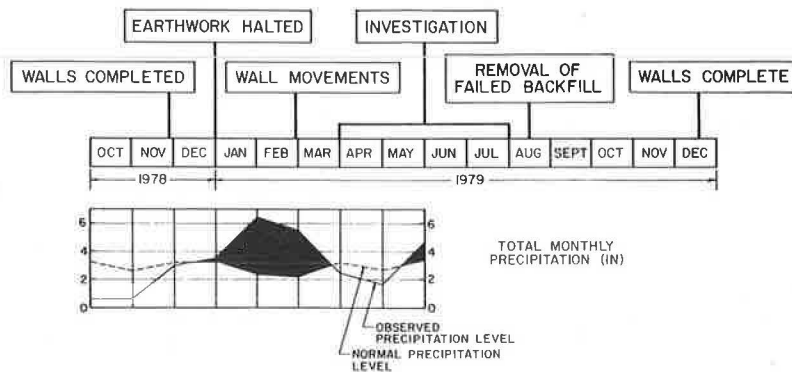
Figure 1. Site plan.

LEGEND
—— Reinforced Earth Wall Facing
///// Reinforced Earth Backfill
\\\\ Reinforced Earth Exhibiting Most Damage
⊕ Location of Hand Dug Sample Hole
⊗ Boring Location

WALL No. 10
WALL No. 9
WALL No. 8
WALL No. 7
WALL No. 6
WALL No. 1
WALL No. 11
WALL No. 12
WALL No. 13
WALL No. 14

TH-13
TH-12
TH-1A
TH-1
TH-2
TH-3

Figure 2. Sequence of events.

TOTAL MONTHLY PRECIPITATION (IN)

OBSERVED PRECIPITATION LEVEL
NORMAL PRECIPITATION LEVEL

tube samples taken at test holes TH-6, TH-9, and TH-10. Hand-excavated bag samples were obtained at test holes 11-14, where test locations were inaccessible to truck-mounted drilling equipment.

Composite grain size distribution curves were plotted for each test hole location. Comparison of these curves indicated that similar grain size distribution curves were obtained by auger cuttings,

Figure 3. Wall damage.

undisturbed samples, and hand excavations. Also, the majority of the hand-excavated samples showed that less than 7 percent of the sample by weight was larger than the 1-1/2-in. sieve size. Therefore, grain size distribution curves for all of the samples should be considered representative of the in situ soils at that location.

A detailed set of testing was conducted, including field sampling, moisture contents, Atterberg limits, unit weights, Proctor compaction tests, and grain size analyses. The results of these tests are summarized in Table 1. The cause of the problem is best shown in Figure 4. The Reinforced Earth walls that exhibited the most severe damage were composed of excessively wet fill soils with a high fines content.

The investigation revealed that a significant portion of the Reinforced Earth backfill was not within the project gradation specifications. In the areas of severe wall distress, the backfill contained well over 30 percent and up to 50 percent fines. Hydrometer analyses of these soils also indicated that the majority of the backfill contained more than 15 percent finer than the 15 μm size, which has been shown by others to be the point where fines control the frictional nature of the soil (1).

Plasticity limits of the backfill were also outside of project specifications. Liquid limits ranged from 23 to 40 for samples with 15 percent or

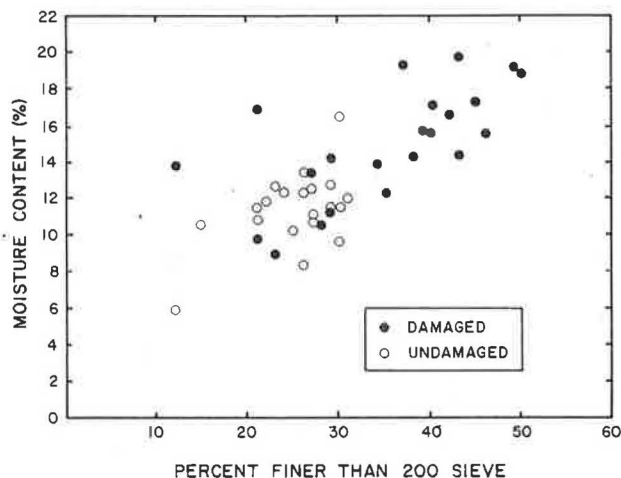Table 1. Classification properties for Reinforced Earth backfill.

| Test | Sample | Depth (ft) | Percentage Finer Than | | | Natural Moisture (%) | Limits | | Optimum Moisture (%) | Maximum Density[a] (lb/ft³) |
			No. 4	No. 200	15 μm		Liquid Limit	Plasticity Index		
TH-1	1	0-5	37	12		5.8				
TH-1	2	5-10	86	30		11.4				
TH-1	3	10-15	62	21		11.4				
TH-1	4	15-20	59	23		12.6				
TH-1	5	20-25	64	29		12.7				
TH-2	1	0-5	80	25		10.2				
TH-2	2	5-10	77	30	20	11.6				
TH-2	3	10-15	74	29		11.5	25	8		
TH-2	4	15-20	65	26		13.4				
TH-3	1	0-1	54	26		8.2				
TH-3	2	1-5	76	27		12.5				
TH-3	3	5-10	78	27		11.2				
TH-3	4	10-15	83	29		11.3				
TH-4	1	0-3	26	12		13.9				
TH-4	2	3-6	92	46	37	15.7	40	20		
TH-4	3	6-10	82	40	31	15.4	34	13		
TH-5	1	0-3	62	29		11.1				
TH-5	2	3-6	89	38		14.1				
TH-5	3	6-9	67	29	22	14.1	33	15		
TH-5	4	9-13	83	43		19.7				
TH-6	1	0-3	63	21		16.8				
TH-6	2	3-6	93	50	39	18.9	39	16		
TH-6	3	6-9	90	49		19.1			13.4	117.9
TH-6	4	9-11	71	34		13.9	33	12		
TH-6	5	11-15	77	39		15.7			13.8	119.5
TH-7	1	0-2	46	15	8	10.5	23	6		
TH-7	2	2-7	65	22	15	11.9	30	13		
TH-7	3	7-12	76	27		11.7				
TH-7	4	12-17	69	26		12.3				
TH-8	1	0-5	61	21		10.7				
TH-8	2	5-10	84	30	20	9.6	24	8		
TH-8	3	10-15	79	31		12.0				
TH-9	1	0-5	78	28	18	10.6				
TH-9	2	5-9	76	27		13.3	28	11	11.0	123.9
TH-9	3	9-11		45		17.3	36	NP		
TH-9	4	11-15	90	43		14.6	35	15	13.7	118.3
TH-9	5	15-20	84	42	30	16.5				
TH-10	1	0-3	66	21		9.7				
TH-10	2	3-6	63	23	17	9.0	26	6	10.1	124.5
TH-10	3	6-8	58	21		9.9	38	13		
TH-10	4	8-11	86	35		12.3			11.9	122.1
TH-11	1	0-2	78	40	22	17.1	32	7		
TH-12	1	0-2	71	37		19.2				
TH-13	1	0-2	68	30		16.5				
TH-14	1	0-2	55	24		12.1				

[a]All Proctors performed in accordance with ASTM D698.

greater passing the No. 200 sieve. Plasticity indices ranged from 6 to 20.

The shear strength of the backfill was estimated from conventional laboratory tests performed on samples that had different fines content. The tests consisted of classification testing as well as tri-

axial shear tests and direct shear tests. Test results are summarized in Table 2.

In addition, strip pull-out capacity was determined for each soil type at various confining pressures. The pull-out tests were performed in a large direct shear box. A diagram of the test apparatus is shown in Figure 5. The shear box accommodates a 3-ft-square, 19-in.-thick sample. The lower half of the box is stationary and is attached to the reaction frame. The upper half of the box consists of 9-in. steel channels and is separated from the rest of the apparatus by 1-in.-diameter steel ball bearings. The normal pressure is applied by nine calibrated springs restrained between two rigid plates. The uppermost plate is bolted to six threaded rods around the perimeter of the box, which are anchored to the base of the apparatus.

Slots for the reinforcing strips were cut in both the upper and lower halves of the box approximately 3 in. from the mid-height of the sample. The reinforcing strips were stressed by jacking against a reaction frame placed across the sides of the box at a deformation rate of approximately 0.10 in./min. The shear load was measured by a load cell positioned between the jack and the reaction frame. Dial gages attached to a stationary reference beam were used to measure strip movement.

Test results are summarized in Figure 5. Compaction levels and moisture contents used to prepare the samples for testing were similar to those levels

Figure 4. Moisture content and percentage fines for damaged and undamaged walls.

Table 2. Residual soil strength property summary.

| Sample Source | Sample No. | Classification | | | Compaction | | Direct Shear | | Triaxial Shear | | Test Density (lb/ft^2) | Test Moisture (%) |
		Liquid Limit	Plasticity Index	Percent Fines	Optimum Moisture (%)	Max.[a] Density (lb/ft^3)	C (lb/ft^2)	ϕ' Degrees	C (lb/ft^3)	ϕ' Degrees		
Project backfill	1	33	NP	23	10.1	124.5	600	33	175	32.9	115.3	13.1
	2	26	NP	26	11.0	124.0	280	34	100	31.4	118.3	11.8
	3	34	30	41	15.7	114.0	0	39	0	36.9	109.0	17.8
Related testing of residual silts	4	44	35	66	18.0	106.5	0	35			98.3	21.9
	5	63	NP	73	30.0	86.0	500	34			86.8	28.4
Related testing of residual sands	6	20	18	11	9.9	128.4	400	47			122.3	9.7
	7	20	18	11	9.9	128.4	500	39.5			124.0	11.8

[a]ASTM D698

Figure 5. Strip pull-out testing device.

(A) 30 TON HYDRAULIC JACK
(B) JACK REACTION FRAME
(C) RIGID UPPER REACTION PLATE
(D) 6-INCH DIAMETER SPRINGS
(E) 3/4-INCH DIAMETER THREADED RODS

(F) RIGID LOWER REACTION PLATE
(G) 3'x3'x1/4" STEEL PLATE RESTING ON SAMPLE
(H) SLOTS FOR REINFORCING STRIPS
(I) 1-INCH DIAMETER STEEL BALL BEARINGS
(J) STATIONARY LOWER HALF OF SHEAR BOX
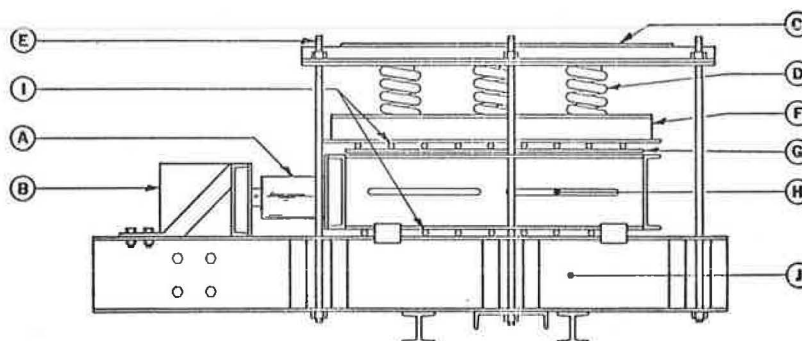
observed from field testing of the backfill. The strip pull-out capacity has been reported in terms of the maximum shear stress applied to the strip divided by the strip normal pressures. This value is termed the apparent friction coefficient (f*).

All samples tested exhibited a significant decrease in f* with increased fines content. The apparent friction coefficient of Reinforced Earth strips in soils with 40 percent fines was observed to be a factor of 2 less than that for soils with 25 percent fines.

An evaluation of the as-built condition of the Reinforced Earth wall was based on these test results. The reduced pull-out capacity of the backfill soils and the possibility that hydrostatic pressures may have developed within the backfill due to poor drainage is sufficient to produce a near-failure condition. Wall movement was not noted in areas where the Reinforced Earth backfill soils were determined to contain less than 25 percent fines. An acceptable safety factor against strip pull-out was back-calculated for these wall sections based on the higher values of apparent friction coefficient available.

Figure 6. Strip pull-out capacity tests with increasing fines content.
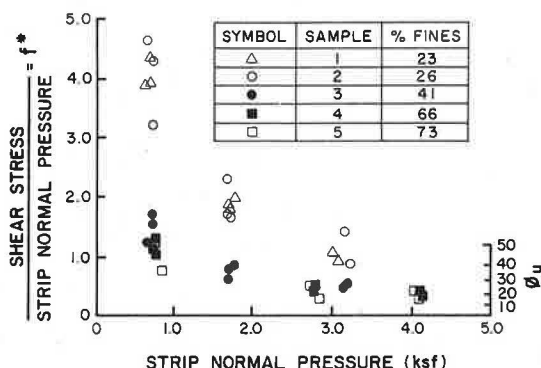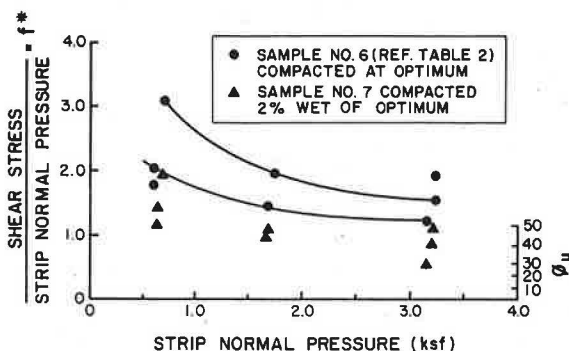
Figure 7. Strip pull-out capacity with increasing moisture content.

Based on the investigation, the areas of Reinforced Earth backfill with more than 25 percent fines were identified, excavated, and replaced with select backfill. The fines content of the new backfill was limited to 25 percent. Most of the concrete panels were reused; however, many of the reinforcing strips were damaged during excavation.

RELATED TESTING

This project provided an opportunity for test results to be compared with previous testing of residual soils. In the past the Reinforced Earth Company has conducted research into the pull-out capacity of ribbed reinforcing strips subjected to variations in fines content and moisture conditions for various residual soils. A summary of the tests previously conducted on residual soils is also shown in Figures 6 and 7.

The apparent friction coefficient (f*) varies considerably with the normal pressure applied to the strip. This trend is observed for all compacted soils. High f* values at low confining pressures are the result of dilatancy in soils that are granular and to some extent to locked-in compactive stresses that cause the soil to be heavily overconsolidated. At higher normal pressures the f* approaches a limiting value. At all pressures the effect of fines content is pronounced. Between 30 and 40 percent fines there is a drastic reduction in the value of f*. Within this range the fine-grained portion of the soil becomes dominant and controls the strength characteristics. It is also evident that the same trend of decreasing f* occurs with increasing fines content from 40 to 70 percent; however, relatively, the effect is much less.

Table 3 is a summary of laboratory direct shear tests (quick tests) performed on French soils to determine short-term internal friction of sand with increasing percentages of fines. Quick tests were performed to compare with results of pull-out tests on reinforcing strips. All samples were compacted to optimum conditions. Some samples were tested at optimum conditions whereas others were saturated before shear.

Figure 8 compares these test results (dashed lines) with those of similar tests performed on a clay-sand mixture without any silt component (solid line). The ratio of ϕ/ϕ_{ou} is shown as a function of the proportion of fines. The value ϕ_{ou} is the angle of internal friction of the saturated soil containing only sand. The value of ϕ_u is that of the saturated soil consisting of sand and fines. Fines has been interpreted in one case as the amount of clay and silt in the mixture. A second interpretation of the same test results define fines as the amount of clay grouping the silt with the sand skeleton.

The soils exhibit a marked reduction in strength; more than 20 percent are finer than the 15 μm size. The curves also indicate that little or no reduction in strength occurs for soils with less than 10 percent passing the 15 μm size. Only

Table 3. Property and strength summary of laboratory soil mixtures.

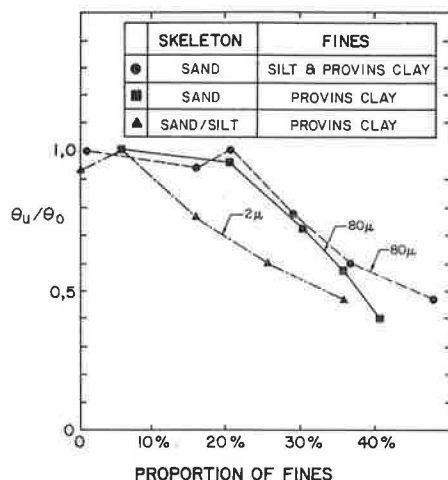| Sample	Percentage Passing			Liquid Limit, W_L	Plasticity Index, IP	Shear Test Under Optimum Conditions		Shear Test on Soil Compacted to Optimum and then Saturated	
	<80 μm	<15 μm	<2 μm			ϕ	C(kPa)	ϕ	C(kPa)
M0	14	6	3			36	12	33	0
M5	19	10	7			36	8	35	3
M15	26	19	15	19	6	36	3	27	34
M25	34	27	23	23	10	30	37	21	40
M35	41	34	31	29	15	17	51	17	44
M100	97	86	82	93	58	16	131	0	95

Figure 8. Strength reduction with fines.

Figure 9. Moisture density curves for residual soils tested.
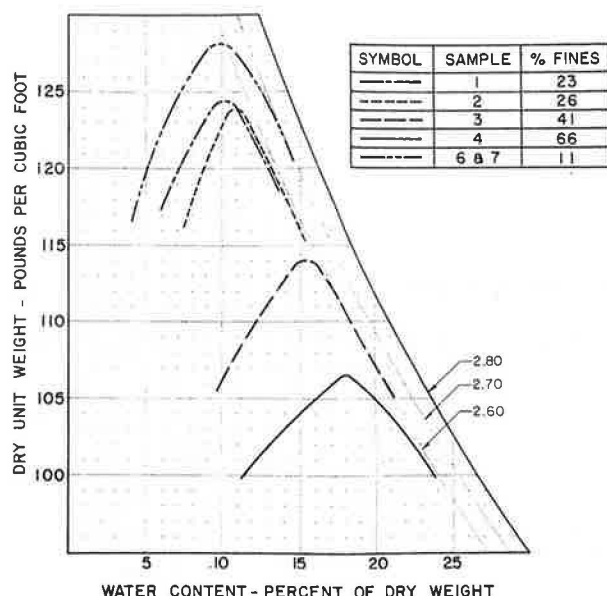
minor strength loss was observed for soils with 15 percent finer than the 15 μm size. The departure of the silt-sand skeleton and clay fines mixture from the other soils confirms that silt size particles should be grouped with the clay fraction rather than the sand fraction.

A series of tests conducted on a 6-m-high test wall completed in 1981 in a Reinforced Earth test facility confirmed a reduction in pull-out capacity when the soils were saturated before testing. With increasing fines the reduction due to saturation was greater. Within the Reinforced Earth backfill specification guidelines the reduction ranged up to approximately 30 percent. Beyond the specification limits (more than 15 percent passing the 15 μm size) the reduction ranged up to 70 percent.

The effect of saturation can also be seen from these test results. The percentage of strength reduction with saturation is increased with increasing fines. The point at which the frictional strength component is controlled by the fine-grained materi-

als appears to occur between 10 and 20 percent passing the 15 μm size. This trend is apparently valid for both partly saturated and fully saturated soils.

A practical application of these trends can be related to the compaction moisture content. Figure 7 is a summary of f* for two samples of a micaceous residual sand from Virginia compacted at slightly different moisture contents. The effect is a significant decrease in f* with a compaction moisture content only 2 percentage points above optimum. Optimum moisture is within 3 percentage points of saturation. Consequently, this soil is sensitive to moisture variations. One explanation may be the effect of mica in the soil matrix. These soils were derived from in situ weathering of the Wissahickon schist. The test samples appeared highly micaceous based on touch and texture. Soils such as these can be difficult to compact even at optimum moisture content (4). The moisture density relations shown in Figure 9 are typical of many residual soils. The optimum moisture content is relatively high, near the zero air voids curve. Soils compacted at or slightly wet of optimum moisture are nearly saturated and, therefore, are sensitive to moisture variations. Soils such as these will exhibit a marked reduction in strip pull-out capacity if compacted wet of optimum.

CONCLUSIONS

The study shows that fines content and moisture content are important factors when constructing Reinforced Earth in residual soils. Between 10 and 20 percent passing the 15 μm size, the fine-grained portion of the fill controls the desired strength properties. The use of Reinforced Earth backfill with a higher percentage of fines can result in a significant reduction in strip pull-out capacity and decrease the internal stability of the wall. The reduction in frictional strength with increasing percentage of fines is even more pronounced in saturated soils.

Caution should be exercised when using residual soils as Reinforced Earth backfill. The fines content of residual soils is subject to large variations over small distances. Also, coarse-grained highly-micaceous sands common to the residual soils of the Piedmont region exhibit a marked sensitivity to moisture and significant strength reduction with increased compaction moisture content. The combination of moisture sensitivity and highly variable fines content requires strict quality control during construction to avert problems in these soil types.

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