Cement-Modified Backfills for Mechanically Stabilized Earth Walls with Built-In Facing

V. Ramana Murty[1] and G. V. Praveen[2]

Abstract: A field study was undertaken to evaluate the performance of model geotextile-reinforced mechanically stabilized earth walls constructed using locally available marginal backfill soils without and with cement modification. Cyclic plate load tests were carried out on the constructed walls both at optimum moisture content and in fully wet conditions in the case of plain backfills and in fully wet condition for cement-modified backfills. The performance and utility of the proposed built-in soil cement facing with folded-back geotextile layers were also examined. The reduction in load-carrying capacity of walls upon wetting could be compensated by cement modification of marginal backfills while maintaining the pullout resistance of reinforcing layers with nominal variation in the flexibility of walls. The performance of model walls constructed using cement-modified marginal backfills is found to be even superior to the wall constructed using free draining sand backfill in terms of higher load-carrying capacity with reduced lateral facing deformations. It was observed that the geotextile-reinforcing layers in marginal backfills also facilitate the internal drainage.

DOI: 10.1061/(ASCE)0899-1561(2009)21:7(343)

CE Database subject headings: Soil stabilization; Walls; Backfills; Cements; Geotextiles; Cyclic loads; Pull-out resistance.

Introduction

Mechanically stabilized earth, popularly known by its trade name "reinforced earth," has gained universal acceptance for a variety of civil engineering applications. A new era began in this technology with the advent of geosynthetic-reinforcing materials as an efficient alternative to other reinforcing materials (Hausmann 1990; Koerner 2000). Despite the wide appreciation of the technique for its versatility, in recent years, few problems and failures of reinforced soil structures were reported (Bathurst and Benjamin 1990; Rowe 1997; Yoo et al. 2004; Ma and Wu 2004, Yoo and Jung 2006; Sahadat and Victor 2007). The reasons for their failure were attributed to the use of inappropriate backfill materials, difficulty in facing connections, and sometimes, poor compaction control (Cousens and Pinto 1996; Holtz 2001; Suah and Goodings 2001). It was felt that the use of marginal soils as backfill in reinforced soil construction could be recommended if comprehensive internal drainage could be provided (Wang and Wang 1993; Zimmie et al. 2005; Goel 2006). Further, it was also opined that cohesive-frictional soils could be a convenient compromise between the technical benefits of cohesionless soils and economic advantages of cohesive soils (Ingold 1981; Wang and Wang 1993; Keller 1995; Swami Saran 2006). The use of electrokinetic geosynthetics to aid drainage in cohesive backfills (Glendinning et al. 2005) and preloading and prestressing (Tatsuoka 2002) to make reinforced backfill very stiff and elastic were suggested in recent years. However, these techniques involve stringent quality control and technical difficulties, especially with large-scale works. It was also felt by some researchers (Gill and Bushell 1992; Marchal et al. 1996; Lawson 2003; Tatsuoka 2004; Mohammad and Mohammad 2006) that the cementitious modification of backfill materials could offer a promising lasting performance of reinforced soil structures. The difficulty in the erection of a facing and its connection to reinforcement, and also a few connection failures of mechanically stabilized earth (MSE) walls were reported by other investigators (Bolton and Pang 1983; Collin and Berg 1993; Gourc 1996; Collin 2001; Goel 2006). An alternative method of constructing a built-in soil-cement facing with folded-back geotextile-reinforcing layers to overcome these difficulties is also presented in this paper.

This paper presents the experimental work carried out to study the behavior of model nonwoven geotextile-reinforced soil walls constructed using plain and cement-modified locally available marginal backfill soils. Also, the performance of a built-in soil-cement facing adopted in the construction of model walls was investigated by measuring the facing deformations during load testing. Further, the pullout behavior of the geotextile was also examined in uncemented and cement-modified backfills to understand its pullout resistance under different test conditions.

[1]Assistant Professor, Dept. of Civil Engineering, National Institute of Technology, Warangal 506 004, India. E-mail: vrm_nitw@yahoo.com

[2]Research Scholar, Dept. of Civil Engineering, NIT, Warangal 506 004 India. E-mail: praveensrec@yahoo.co.in

Note. This manuscript was submitted on December 21, 2006; approved on December 29, 2008; published online on June 15, 2009. Discussion period open until December 1, 2009; separate discussions must be submitted for individual papers. This technical note is part of the *Journal of Materials in Civil Engineering*, Vol. 21, No. 7, July 1, 2009. ©ASCE, ISSN 0899-1561/2009/7-343–348/$25.00.

Materials and Methodology

Materials

Backfill Soils

Three locally available soils were used as backfills, and their properties were determined as per the Bureau of Indian Standards

J. Mater. Civ. Eng., 2009, 21(7): 343-348

Table 1. Properties of Backfill Soils

Property	Soil-1 (sand)	Soil-2 (murrum)	Soil-3 (upland soil)
Specific gravity	2.65	2.66	2.67
Grain size distribution			
Gravel (%)	5	10	2
Sand (%)	95	59	58
Silt (%)	—	21	24
Clay (%)	—	10	16
Atterberg limits			
Liquid limit, w_l (%)		38	36
Plastic limit, w_p (%)	NP[a]	19	17
Shrinkage limit, w_s (%)		14	14
Unified soil classification	SP[b]	SC[c]	SC[c]
Compaction properties			
OMC (%)	12	15	16.5
MDD[d] (Mg/m^3)	1.58	1.82	1.83
Shear strength parameters			
(i) UU[e] condition			
c_u[f] (kPa)	—	55	57
ϕ_u[g]	—	16°	14°
(ii) CD[h] condition			
c'[i] (kPa)	0	10	15
ϕ[j]	41°	40°	39°
Coefficient of permeability, k (cm/s)	1.25×10^{-3}	8.89×10^{-5}	2.48×10^{-6}

[a]NP=nonplastic.
[b]SP=Poorly graded soil.
[c]SC=clayey sand.
[d]MDD=maximum dry density.
[e]uu=unconsolidated undrained.
[f]c_u=undrained cohesion.
[g]ϕ_u=undrained angle of internal friction.
[h]CD=consolidated drained.
[i]c'=effective cohesion.
[j]ϕ'=effective angle of internal friction.

[SP 36 (Part 1) (1987)]. The properties of these soils are given in Table 1. Soil-2 (murrum) and Soil-3 (upland soil) were chosen to simulate marginal backfills with a higher content of fines and low permeability. In order to overcome the ill effects of plastic fines of marginal soils, cement modification was adopted, and the properties of cement-modified soils are given in Table 2. Though the soils became nonplastic with 2% cement content, 3% cement content was used to account for the possible nonuniform mixing of cement content while handling considerable quantities of materials used in this investigation.

Cement

Ordinary Portland cement of 53 grade was used to modify the marginal backfill soils and also to form the built-in soil-cement facing.

Geotextile

Nonwoven geotextile (Fibertex G-100) was used as a reinforcement in this investigation, and its properties as given by the manufacturer are: weight=100 g/m^2; thickness at 2 kPa =0.6 mm; static puncture (California bearing ratio test)=940 N; elongation=55%; tensile strength (longitudinal direction) =4.0 kN/m; tensile strength (transverse direction)=5.0 kN/m; elongation at break=40–50%; dynamic cone drop=40 mm; permeability=0.13 m/s; permittivity=2.6 s^{-1}; water flow =130 l/s/m^2; k_{Darcy} at 2 kPa=10^{-3} m/s; pore size, $O_{90\%}$ =110 μm.

Test Procedures

Pullout Tests

In order to understand the pullout resistance of the geotextile reinforcement (Fibertex G-100) embedded in different backfills, pullout tests were carried out in a modified direct shear box of size 60×60×20 mm. The geotextile strip of 25 mm wide and 100 mm long was placed over the respective compacted fill materials in the lower half of the shear box, and then the same fill was compacted in the upper half of the shear box to its maximum dry density. The projected part of the geotextile strip was attached to a clamping system, which in turn was connected to a tension-proving ring. Subsequently, these strips were pulled out at the rate of 1.25 mm/min at both optimum moisture content (OMC) and in fully wet condition under normal stresses (σ) of 10, 20, and 30 kPa. The pullout stress versus pullout deformation plots for all the test conditions was drawn, and from these plots the peak

Table 2. Properties of Soil-Cement Mixes

Property	Percent cement in Soil-2				Percent cement in Soil-3			
	0%	2%	3%	4%	0%	2%	3%	4%
Atterberg limits (immediately after adding the cement)								
Liquid limit, w_l (%)	38	37	36	34	36	35	34	32
Plastic limit, w_p (%)	19	20	21	22	17	17	18	20
Atterberg limits (at 3-day curing period)								
Liquid limit, w_l (%) / Plastic limit, w_p (%)	—	NP	NP	NP	—	NP	NP	NP
Unconfined compressive strength (UCS) at 3-day curing period (kPa)	76	275	359	669	74	261	334	608

[a]NP=nonplastic.

J. Mater. Civ. Eng., 2009, 21(7): 343-348

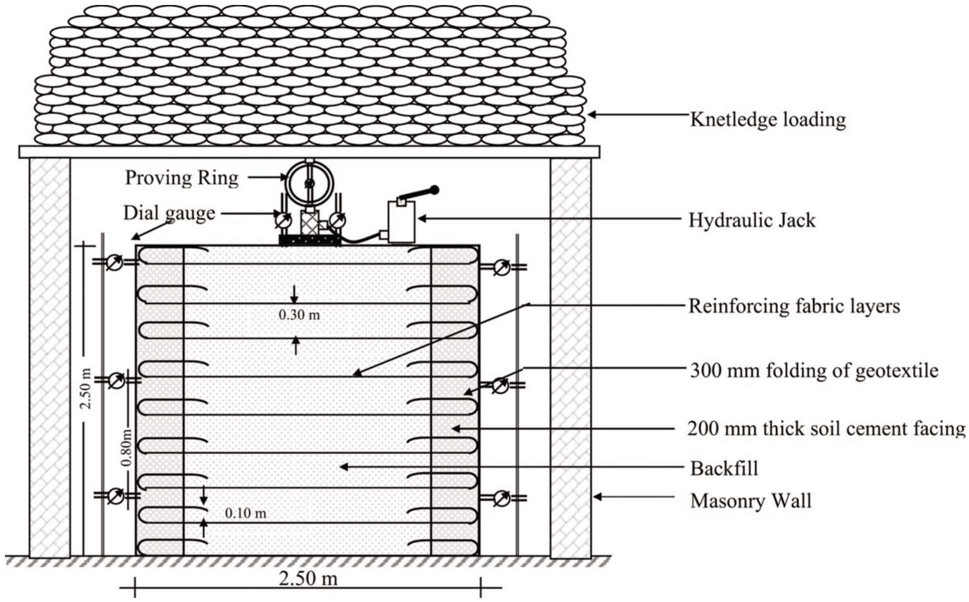

Fig. 1. Schematic of experimental setup for load testing on geotextile-reinforced (Fibertex G-100) model wall

pullout resistance (p) values were noted to calculate the interface friction angle ($\delta = \mathrm{Tan}^{-1}(p/\sigma)$) between the respective fill materials and geotextile reinforcement.

Cyclic Plate Load Tests

Construction of Model Walls. Model MSE walls of 2.50 m wide and 2.50 m high were constructed using geotextile reinforcement at 0.30 m vertical spacing with folded backs at the facing (Fig. 1). Four MSE walls, two for each marginal backfill soil (Soil-2/Soil-3) without cement modification were constructed for load testing at both OMC and in a fully wet condition, respectively. Two more walls were constructed again using Soil-2 and Soil-3, respectively, as backfills after admixing them with 3% cement content. In the case of the wall constructed using sand (Soil-1) as backfill, no cement modification was adopted, as it was nonplastic, free draining, and frictional material, for which the load testing was carried out only at OMC. In order to form the vertical facing for these walls, specially fabricated steel-form shutters were used. The respective fill materials were placed over each geotextile layer and compacted using a 2-t stone roller at its OMC. In order to form a 200 mm thick built-in soil-cement facing, the same backfill soil was mixed with 10% cement content and compacted near the facing simultaneously with the placement of backfill, and the geotextile layer was folded back as shown in Fig. 1. Further placement of backfill and the formation of the facing were continued up to the top of first lift, and then the next layer of geotextile was placed over the compacted soil layer, and the procedure was repeated until the construction of the wall was completed.

Load Testing. In the case of MSE walls constructed using marginal backfills without cement modification, cyclic plate load tests were carried out at both OMC and in fully wet conditions. For the walls constructed using cement-modified backfills, the load testing was performed at a 7-day curing period by inundating the walls to simulate the fully wet conditions. Load was applied centrally over the top surface of the wall through a 300 mm diameter steel plate with the help of a hydraulic jack and a proving ring of 20 ton capacity reacting against the knetledge-loading frame (Fig. 2). A seating load of 5 kPa was applied initially to ensure proper contact of the loading plate over the compacted soil surface, and then the dial gauge readings were set to zero. Later, the load was applied in increments of 25 kPa, and each increment was maintained until the settlement was less than 0.10 mm/h up to the first loading cycle of 100 kPa and then unloaded in 50 kPa decrements. Again the reloading was done to the next cycle of 200 kPa while measuring the settlements and unloaded as above. The testing was continued until failure of the respective walls and the cyclic load—settlement plots were drawn for different test conditions.

Results and Discussion

Pullout Behavior

The results obtained from pullout tests carried out in a modified direct shear box on the nonwoven geotextile fabric embedded in

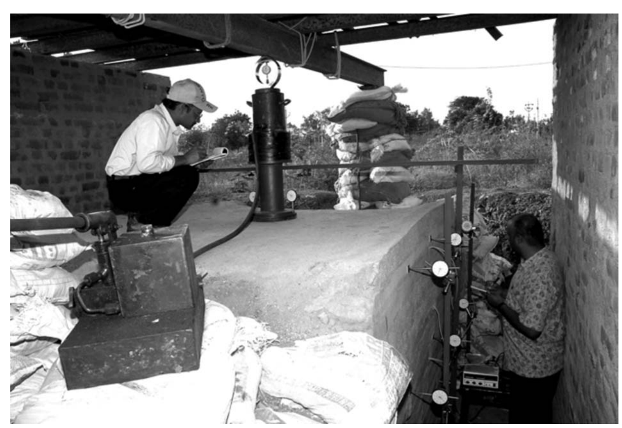

Fig. 2. Experimental setup for load testing on geotextile-reinforced (Fibertex G-100) model wall

J. Mater. Civ. Eng., 2009, 21(7): 343-348

Table 3. Soil-Geotextile Interface Frictional Properties under Different Test Conditions

	Values of normal stress (σ) (kPa)		
Interface frictional properties	10	20	30
Soil-1 (at OMC and MDD)			
Peak pullout stress (*p*) (kPa)	14	13	26
Interface friction angle (δ)	54°	52°	50°
Soil-1 (saturation)			
Peak pullout stress (*p*) (kPa)	13	25	36
Interface friction angle (δ)	52°	51°	50°
Soil-1+3% cement			
Peak pullout stress (*p*) (kPa)	21	31	38
Interface friction angle (δ)	64°	57°	52°
Soil-2 (at OMC and MDD)			
Peak pullout stress (*p*) (kPa)	10	16	22
Interface friction angle (δ)	45°	38°	36°
Soil-2 (saturation)			
Peak pullout stress (*p*) (kPa)	7	10	15
Interface friction angle (δ)	35°	27°	26°
Soil-2+3% cement			
Peak pullout stress (*p*) (kPa)	25	36	50
Interface friction angle (δ)	68°	61°	59°
Soil-3 (at OMC and MDD)			
Peak pullout stress (*p*) (kPa)	8.40	15	18
Interface friction angle (δ)	40°	36°	31°
Soil-3 (saturation)			
Peak pullout stress (*p*) (kPa)	6	10	12
Interface friction angle (δ)	31°	26°	22°
Soil-3+3% cement			
Peak pullout stress (*p*) (kPa)	26	39	52
Interface friction angle (δ)	69°	63°	60°

both plain and cement-modified fills are presented in Table 3. It can be observed from this table that the interfacial friction angles between the marginal fills (Soil-2 and Soil-3) and the geotextile are reduced by about 30% upon wetting. The reduction in pullout resistance of geotextile due to the plasticity of marginal soil fills is not only compensated by 3% cement modification but also added further resistance. However, all these values are much higher than the usual range. Further, the variation of interfacial friction angles for different cement-modified fills is observed to be marginal for a given normal stress. These trends could be attributed to the extensibility of geotextile reinforcement, due to which, the testing displacements inevitably include the amount of stretching besides sliding; and also the possibility of formation of a slight wavy pattern of the fabric that mobilizes the passive resistance, whereby, the recorded behavior can be skeptical. Previous investigators also reported such behavior with flexible reinforcing materials (Ingold 1983; Kate et al. 1988; Rao and Pandey 1988; Voottipruex and Bergado 2003).

Pressure-Settlement Behavior

From the cyclic pressure-settlement plots as obtained from load tests, the maximum settlement for each pressure increment was noted, and using these values, pressure-settlement plots (Fig. 3) were drawn for all the test conditions in order to show their relative behavior. These plots clearly indicate that the marginal backfills suffer from substantial loss of their load-carrying capacity upon wetting due to the presence of more plastic fines. The same soils have become unaffected by wetting upon 3% cement modification and could offer higher load-carrying capacity than the walls built with plain backfills, without significant variation in flexibility of the system.

The values of ultimate bearing capacity and the corresponding settlements for different test conditions were obtained against the intersection points of tangents drawn to the initial and final straight-line portions of pressure-settlement plots (Adams and Collin 1997). From these values, the bearing capacity ratio (BCR) and settlement ratio (SR) for different backfill conditions were calculated (Table 4). The BCR is taken as the ratio of ultimate bearing capacity of reinforced soil walls for a given backfill material without the effect of inundation to the ultimate bearing capacity of the wall affected by the inundation. The ultimate bearing capacity values for the walls constructed with plain backfills and tested at OMC or with cement-modified backfills cured by inundation are taken as unaffected by the inundation. Similarly, the SR is defined as the ratio of settlements corresponding to the ultimate

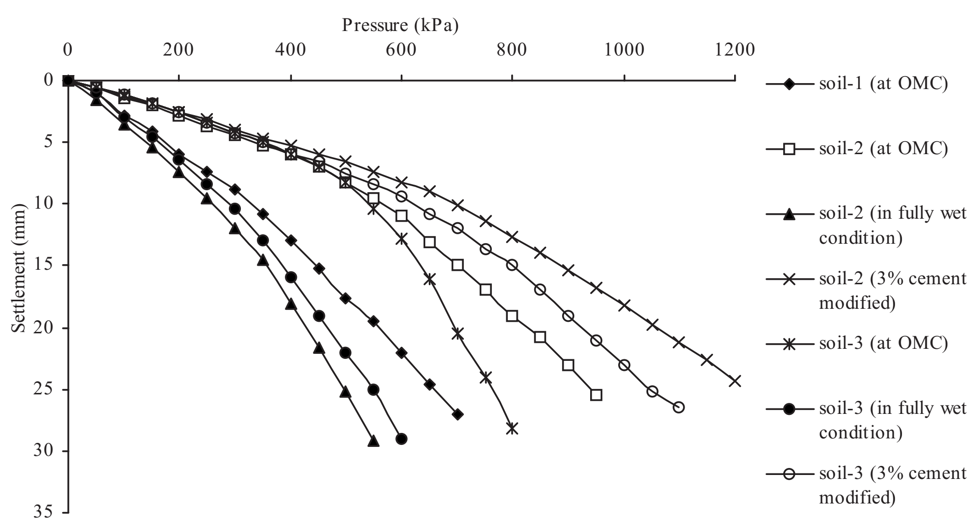

Fig. 3. Pressure-settlement curves for MSE walls under different test conditions

J. Mater. Civ. Eng., 2009, 21(7): 343-348

Table 4. Values of Ultimate Bearing Capacity and the Corresponding Settlements for Different Test Conditions

Geotextile-reinforced backfill	Test condition	Ultimate bearing capacity (kPa)	Settlement at ultimate bearing capacity (mm)	BCR	SR
Soil-1	At OMC	338	9.75	—	—
Soil-2	At OMC	495	7.1	2.04	0.78
Soil-2	After 7-day inundation	242	9	1.00	1.00
Soil-2+3% cement	After 7-day inundation	670	9	2.76	1.00
Soil-3	At OMC	526	7.05	2.02	0.90
Soil-3	After 7-day inundation	260	7.8	1.00	1.00
Soil-3+3% cement	After 7-day inundation	665	9.2	2.55	1.17

bearing capacities for the above conditions. Though the previous investigators (Binquet and Lee 1975; Sakti and Das 1987; Shankaraiah and Narahari 1988) defined the BCR as the ratio of ultimate bearing capacity of reinforced soil to the unreinforced soil for equal settlement, the modified definitions are adopted in the present study to understand the settlement behavior of marginal backfill soils along with their bearing capacity. The previous works carried out by the investigators on sand indicated that there is a shift in ultimate bearing capacity of sand due to the provision of reinforcement with only a nominal variation in its settlement. Others also followed some deviations with regard to the BCR values (Sakti and Das 1987; Das et al. 1998). As can be seen from Table 4, the BCR values of walls constructed using Soil-2 and Soil-3 are increased by about 2.5 to 2.7 times upon cement modification with SR values close to unity. The reduction in load-carrying capacity of walls upon wetting of marginal backfills could be offset by cement modification of such fills. The relatively flatter pressure—settlement plots of walls with cement-modified backfills also reflect their improved performance with nominal variation in flexibility.

Wall-Facing Deformations

The wall-facing deformations were recorded with loading intensity, and the values corresponding to the ultimate loads as given in Table 4 were plotted at different wall elevations for varied test conditions (Fig. 4). It can be seen from this figure that the maximum lateral facing deformations in the fully wet condition of walls with cement-modified marginal backfills are reduced to about one-third of the respective walls with plain backfills, indicating their improved performance. These trends can be supported by the fact that the marginal soils have become unaffected by wetting upon cement modification. The built-in soil-cement facing has not shown any cracking or yielding during load testing that indicates its possible use as an alternative to conventional facings, which of course needs prototype testing before recommending it in practice. The desired aesthetics can also be given to the built-in soil-cement facing by plastering the surface accordingly.

Summary and Conclusions

The use of marginal backfill soils can be made amenable for the construction of MSE walls by modifying them with cement, which helps to alleviate the ill effects of finer fraction on the performance of such walls. The provision of geotextile reinforcing layers in such marginal backfills facilitates internal drainage, which coupled with a nonplastic nature of cement-modified backfills could preserve their strength even under fully wet condition, and the constructed MSE walls have shown improved stability in terms of increased BCRs of about 2.5 to 2.7 with the SRs close to unity. The reduced lateral wall deformations due to cement modification of backfills also indicate the improved performance of MSE walls with little variation in their flexibility. The concept of a built-in soil-cement facing can be a potential alternative to conventional facings, as it does not involve the erection and connection problems that could help in faster construction of MSE walls. However, this aspect of a built-in soil-cement facing needs further

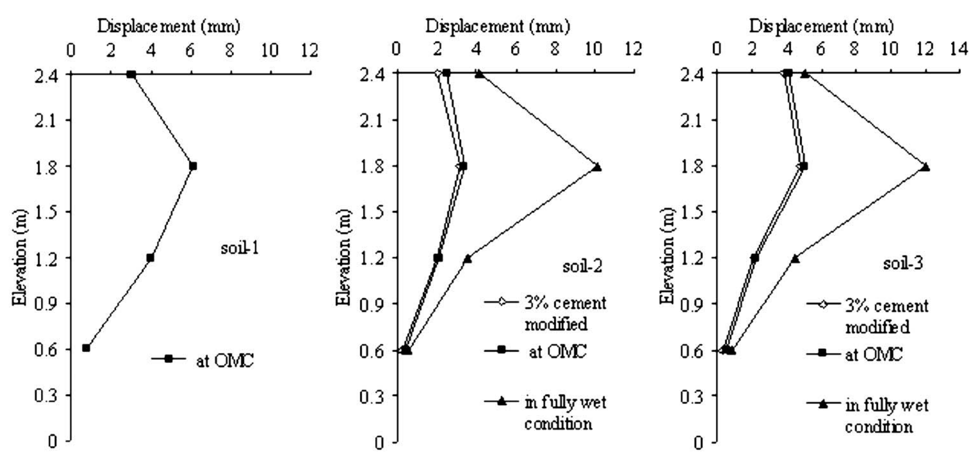

Fig. 4. Horizontal deformation of wall facing

J. Mater. Civ. Eng., 2009, 21(7): 343-348

investigation on prototype walls for its long-term performance, especially for greater wall heights.

References

Adams, M. T., and Collin, J. G. (1997). "Large model spread footing load tests on geosynthetic reinforced soil foundations." *J. Geotech. Geoenviron. Eng.*, 123(1), 66–72.

Bathurst, R. J., and Benjamin, D. J. (1990). "Failure of a geogrid-reinforced soil wall." *Transportation Research Record. 1288*, Transportation Research Board, Washington, D.C., 109–116.

Binquet, J., and Lee, L. K. (1975). "Bearing capacity tests on reinforced earth slabs." *J. Geotech. Engrg. Div.*, 101(12), 1241–1255.

Bolton, M. D., and Pang, P. L. R. (1983). "Collapse limit states of reinforced earth retaining walls." *Geotechnique*, 32(4), 349–367.

Collin, J. G. (2001). "Lessons learned from a segmental retaining wall failure." *Geotext. Geomembr.*, 19(7), 445–454.

Collin, J. G., and Berg, R. R. (1993). "Connection strength criteria for mechanically stabilized earth walls." *Highway Research Record. 1414*, Transportation Research Board, Washington, D.C., 32–37.

Cousens, T. W., and Pinto, M. I. M. (1996). "The effect of compaction on model fabric reinforced brick faced earth retaining walls." *Proc., Int. Symp. on Earth Reinforcement*, Vol. 1, Fukuoka, Kyushu, Japan, 339–334.

Das, B. M., Khing, K. M., and Shin, E. C. (1998). "Stabilization of weak clay with strong sand and geogrid at sand-clay interface." *Transportation Research Record. 1611*, Transportation Research Board, Washington, D.C., 55–62.

Gill, S. A., and Bushell, T. D. (1992). "Reinforced soil—Cement embankment." *Proc., specialty Conf. on Stability and Performance of Slopes and Embankments II*, ASCE, New York, 1493–1504.

Glendinning, S., Jones, C. J. F. P., and Pugh, R. C. (2005). "Reinforced soil using cohesive fill and electrokinetic geosynthetics." *Int. J. Geomech.*, 5(2), 138–146.

Goel, R. (2006). "Mechanically stabilized earth walls and reinforced soil slopes: Indian scenario—A comprehensive review." *J. Indian Roads Congress*, 67(1), 51–78.

Gourc, J. P. (1996). "Retaining structures with geosynthetics: A mature technique, but with some questions pending . . ." *Proc., First European Geosynthetics Conf.*, Balkema, Rotterdam, Brookfield, The Netherlands, 27–46.

Hausmann, M. R. (1990). *Engineering principles of ground modification*, McGraw-Hill, New York.

Holtz, R. D. (2001). "Geosynthetics for soil reinforcement." *The 9th Spencer J. Buchanan Lecture*, Texas A&M University, College Station, Tex.

Ingold, T. S. (1981). "A laboratory simulation of reinforced clay walls." *Geotechnique*, 31(3), 399–412.

Ingold, T. S. (1983). "A laboratory investigation of grid reinforcements in clay." *Geotech. Test. J.*, 6(3), 112–119.

Kate, J. M., Venkatappa Rao, G., and Tyagi, S. K. (1988). "Evaluation of soil-reinforcement friction." *Indian Geotech. J.*, 18(2), 154–160.

Keller, G. R. (1995). "Experiences with mechanically stabilized structures and native soil backfill." *Transportation Research Record. 1474*, Transportation Research Board, Washington, D.C., 30–38.

Koerner, R. M. (2000). "Emerging and future developments of selected geosynthetic applications." *J. Geotech. Geoenviron. Eng.*, 126(4), 293–306.

Lawson, C. R. (2003). "Combined technology in Earth reinforcement." *Proc., 12th Asian Regional Conf. on Soil Mechanics and Geotechnical Engineering*, South Asian Geotechnical Society, Singapore, 1–17.

Ma, C. C., and Wu, J. T. H. (2004). "Field performance of an independent full-height facing reinforced soil wall." *J. Perform. Constr. Facil.*, 18(3), 165–172.

Marchal, J. R., Bastick, M., and Belblidia, F. (1996). "Innovative facing for a 24 meter high Terre Armee wall near Pont de Normandie." *Proc., Int. Symp. on Earth Reinforcement*, Vol. 1, Fukuoka, Kyushu, Japan, 421–425.

Mohammad, J. K., and Mohammad, A. (2006). "Durability and mechanistic characteristics of fibre reinforced soil-cement mixes." *Int. J. Pavement Eng.*, 7(1), 53–62.

Rao, G. V., and Pandey, S. K. (1988). "Evaluation of geotextiles-soil friction." *Indian Geotech. J.*, 18(1), 77–105.

Rowe, R. K. (1997). "Reinforced embankment behaviour: Lessons from number of case histories." *Symp. on Recent Developments in Soil and Pavement Mechanics*, Balkema, The Netherlands, 147–159.

Sahadat, M. D. H., and Victor, P. E. O. (2007). "Failure analysis of mechanically stabilized earth wall in Maryland." *Transportation Research Board 86th Annual Meeting* (CD-ROM), Transportation Research Board.

Sakti, P. J., and Das, B. M. (1987). "Model tests for strip foundation on clay reinforced with geotextile layers." *Transportation Research Record. 1153*, Transportation Research Board, Washington, D.C., 40–45.

Shankaraiah, B., and Narahari, R. (1988). "Bearing capacity of reinforced sand beds." *1st Indian Geotextiles Conf. on Reinforced Soil and Geotextiles*, Vol. 1, IIT, Bombay, India, C9–C14.

SP 36 (Part 1). (1988). "Compendium of Indian Standards on soil engineering." Bureau of Indian Standards, New Delhi, India.

Suah, P. G., and Goodings, D. J. (2001). "Failure of geotextile-reinforced vertical soil walls with marginal backfill." *Transportation Research Record. 1772*, Transportation Research Board, Washington, D.C., 183–189.

Swami, S. (2006). *Reinforced soil and its engineering applications*, I.K. International Pvt. Ltd., New Delhi, India.

Tatsuoka, F. (2002). "Geosynthetic-reinforced soil retaining wall as permanent structures." *Proc., Indian Geotechnical Conf.*, Vol. 2, Phoenix Publishing House, New Delhi, India, 681–699.

Tatsuoka, F. (2004). "Cement-mixed soil for trans-Tokyo Bay Highway and railway bridge abutments." *Proc., Geo-Trans 2004*, Geo-Institute of American Society of Civil Engineers, Los Angeles, 18–76.

Voottipruex, P., and Bergado, D. T. (2003). "Pullout and direct shear resistances of hexagonal wire mesh reinforcement in various types of backfills." *Geotechnical Engineering J., Southeast Asian Geotechnical Society*, 34(2), 101–121.

Wang, Y. H., and Wang, M. C. (1993). "Internal stability of reinforced soil retaining structures with cohesive backfills." *Transportation Research Record. 1414*, Transportation Research Board, Washington, D.C., 38–48.

Yoo, C., Jung, H. S., and Jung, H. Y. (2004). "Lessons learned from a failure of geosynthetics-reinforced segmental retaining wall." *3rd Asian Regional Conf. on Geosynthetics*, Vol. 1, Korean Geosynthetics Society, Seoul, Korea, 265–274.

Yoo, C., and Jung, H. Y. (2006). "Case history of geosynthetic reinforced segmental retaining wall failure." *J. Geotech. Geoenviron. Eng.*, 132(12), 1538–1548.

Zimmie, T. F., Pamuk, A., Adalier, K., and Mahmud, M. B. (2005). "Retrofit-reinforcement of cohesive soil slopes using high strength geotextiles with drainage capability." *Geotech. Geologic. Eng.*, 23(4), 447–459.

J. Mater. Civ. Eng., 2009, 21(7): 343-348