TRANSPORTATION RESEARCH
CIRCULAR

Number 444 May 1995

Mechanically Stabilized Earth Walls

TRANSPORTATION RESEARCH BOARD / NATIONAL RESEARCH COUNCIL

TRANSPORTATION
RESEARCH
CIRCULAR

Number 444, May 1995
ISSN 0097-8515

MECHANICALLY STABILIZED EARTH WALLS

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PREFACE

For the past two decades since its inception, soil reinforcement has been widely used for a variety of applications such as retaining walls, embankment slopes, and natural or cut slopes. The beneficial effect on the soil mass has been demonstrated by the successful construction of numerous reinforced soil walls with reinforcement of various configurations and facing elements of various stiffnesses. As a result of this increasing interest, the profession's understanding of the mechanics of reinforced soil has increased significantly in recent years. Design procedures and methodologies are now available for each type of reinforcement and proprietary system. These procedures are based on past experience, results of extensive laboratory model tests, observations on instrumented full-scale structures, and several analytical and numerical studies.

The purpose of this TRB circular is to present a concise description of mechanically stabilized embankment/wall systems so that practicing engineers will have the necessary understanding of design methodologies, applications, and limitations. An attempt is made in this circular to be generic in the explanation of basic principles, while also focusing on differences in the various systems. Construction procedures are discussed for the benefit of designers, resident engineers, and inspectors. A list of references is provided for a more in-depth study of mechanically stabilized embankment/wall systems.

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INTRODUCTION

During the past two decades methods of increasing the stability of constructed soil embankments by using reinforcing elements has received increasing attention. A broad definition of reinforced soil or mechanically stabilized embankments would be the inclusion of reinforcing elements such as straps, bars, welded wire mats, polymer grids, sheets of fabric (geosynthetic) and various anchor systems for the purpose of improving the mechanical properties of the soil mass. All of the system elements including the backfill must receive adequate attention during the design and construction stages.

The concept of soil reinforcement has a well established history dating back to biblical times. However, modern techniques for mechanically stabilizing or reinforcing soil were only introduced about 20 years ago (Vidal 1966, 1969). Vidal's method is known as Reinforced Earth® and it was first used in France. The first use of Reinforced Earth® in the United States was a 55-foot high retaining wall constructed by the California Division of Highways as part of a landslide correction scheme on California Highway 39 near Los Angeles (Chang, Forsyth and Smith, 1972). Since this first application of Reinforced Earth® in the United States in 1972, many other methods of reinforcing soil embankments, foundations, and subgrades have been introduced. These other methods include various types of metal grid systems, polymer grid systems, anchor systems and geosynthetics. Geosynthetics have experienced the highest growth rate in terms of the number of geosynthetics that are now available. In 1976, there were only about five or six different geosynthetics available; today there are more than 400 types of geosynthetics available on the international market.

BACKGROUND

In the past 10 years many new reinforcement systems have been introduced, several important improvements have been made in the Reinforced Earth® method and thousands of reinforced soil embankments and walls of various types have been constructed in the United States. Furthermore, the profession's understanding of the mechanics of reinforced soil methods has increased significantly. This improved understanding has resulted from many field instrumentation programs and from several theoretical studies using the finite element method. In a study sponsored by NCHRP, Mitchell and Villet (1987) have made a comprehensive review of the current literature on "Reinforcement of Earth Slopes and Embankments" and the reader is referred to their work for an in-depth discussion of the various soil reinforcement methods. Table 1 summarizes the currently available soil reinforcement systems. A technical evaluation process for selection of a particular type of earth reinforcement system is outlined by Cheney (1990).

MECHANICS OF SOIL REINFORCEMENT

Reinforced soil structures are constructed in a manner that produces a structure of alternating layers of soil and reinforcing elements as shown in Figure 1. In general, the spacing between reinforcement layers varies from about 1 foot to 2.5 feet. Soil reinforcing systems have three main components: reinforcement elements, backfill material and facing elements (Figure 1). The primary differences between various soil reinforcement systems that are currently available are the materials and configuration of the materials that are used for the reinforcing and facing elements. The specifications for the backfill material that are used with each system depend on the type of reinforcing system. The resulting reinforced soil structures are flexible and can generally accommodate relatively large horizontal and vertical movements without excessive structural distress. The type of facing will put some limitations on the amount of settlement that can be tolerated by mechanically stabilized embankment/wall systems.

Even though different materials are used, the same basic criteria must be employed to design the systems. In general, the basic design procedure for reinforced soil structures is well established (Lee, et al, 1973; McKittrick, 1978; Anderson et al, 61986a; Anderson et al 1986b; Anderson et al, 1987; Anderson and Wong, 1989; Mitchell and Villet, 1987; DiMaggio, 1988; Christopher et al, 1989; Mitchell and Christopher, 1990; Allen and Holtz, 1991) and many successful structures have been designed using these procedures. The basic design criteria for reinforced soil retaining walls involves satisfying: 1) external stability and 2) internal stability.

External Stability

External stability is evaluated by considering the entire reinforced mass as a semi-rigid gravity retaining wall with active soil pressure applied behind the wall as

TABLE 1 COMPARISON OF EARTH REINFORCEMENT SYSTEMS (AFTER MITCHELL AND VILLET, 1987)

Reinforcement Type		Soil Geometry (Slope 30 60, Wall 90)	Soil Type* (Clay .002, Silt .02, Sand .20, Gravel 2.0 mm.)	Soil Transfer Mechanism		Reinforcement Material		Propriety Systems/ Product Names
				Surface Friction	Passive Resistance	Metal	Nonmetal	
STRIP	Smooth	├───┤	├────┤	•		•		Reinforced Earth
							•	
	Ribbed	├───┤	├────┤		├──┤	•		Reinforced Earth
							•	Paraweb
GRID		├────┤	├─────┤		•	•		VSL, MSE, GAS, RSE and Welded Wire Wall
							•	Tensar Geogrids
SHEET		├──┤	├────┤	•			•	Geotextiles
BENT ROD ANCHOR		├───┤	├────┤		•	•		Anchored Earth, Syro Anchored Wall
FIBER		├────┤	├───┤	•		•	•	

* Soil type is based on stress transfer between soil reinforcement. Other criteria may preclude use of some soils for specific applications.

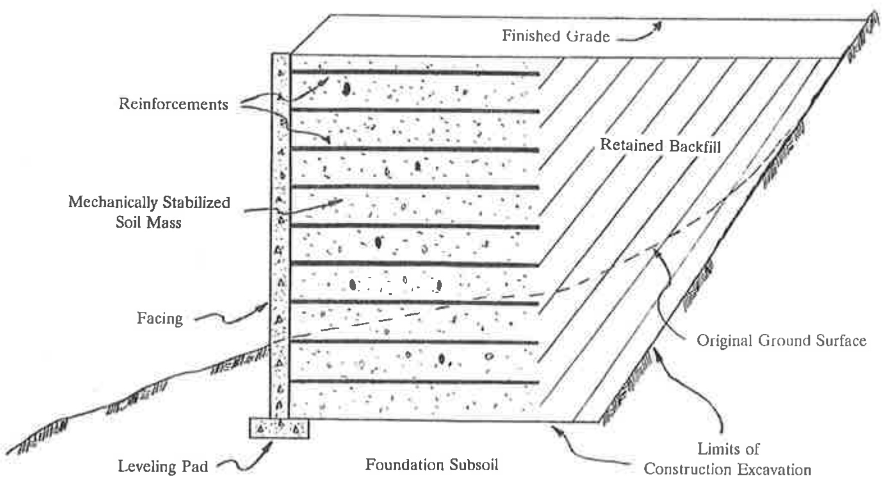
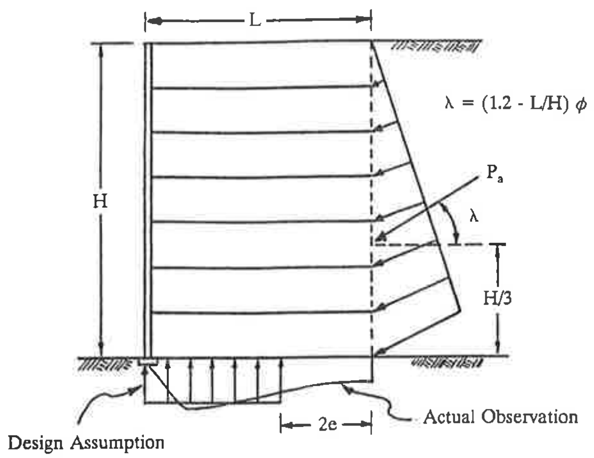


FIGURE 1 Principal components of a mechanically stabilized soil mass.

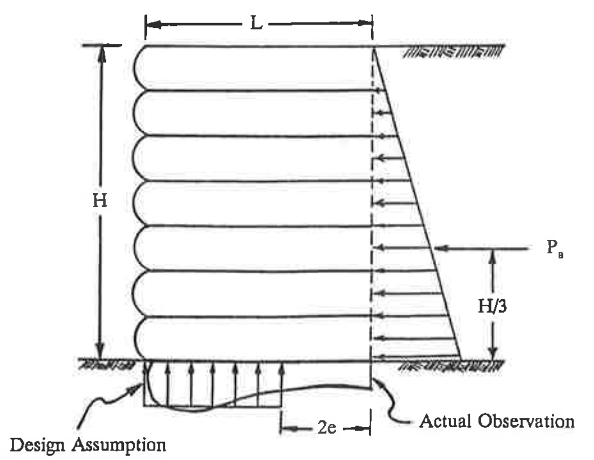
shown in Figure 2. The wall is then checked for the conventional stability criteria of: (1) overturning, (2) sliding, (3) bearing capacity and (4) deep stability (conventional slope stability with a failure surface below the reinforced mass). Figure 3 shows the external stability mechanisms of failure in reinforced soil walls. The sliding requirement for external stability generally governs the overall dimensions of the wall. Deep stability (overall slope stability) can be critical for walls on steep slopes and for soft foundation conditions. Particular attention should be given to deep stability when the wall is being used as a landslide correction scheme.

Internal Stability

The interaction between the reinforcing elements and the soil produces a composite coherent material that can stand unsupported as a retaining wall or steep embankment and can withstand relatively large deformations without structural distress. The manner in



(a) Inextensible Reinforcement



(b) Extensible Reinforcement

FIGURE 2 Active thrust and base pressure distribution on reinforced soil walls.

which stresses are transferred from the soil to the reinforcement depends on the type of system. Most of the currently available systems are inextensible systems in that the strains that are required to mobilize the full strength of the reinforcing elements are much smaller than the strains required to mobilize the strength of the soil. Extensible systems, on the other hand, require relatively large strains to mobilize the strength of the reinforcement and thus larger internal deformations generally occur in these types of walls and embankments. The actual mechanism of stress transfer in the two different systems is probably somewhat different but the same general internal stability design criteria must be satisfied.

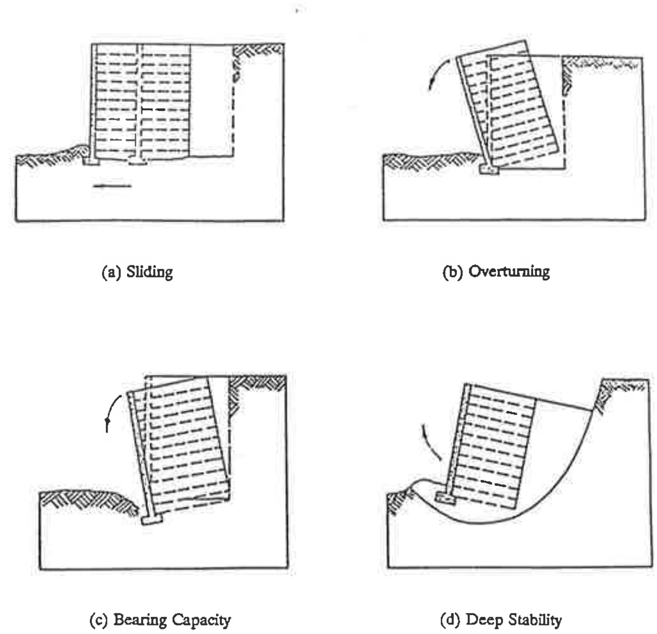


FIGURE 3 External stability mechanisms of failure in reinforced soil walls (after Christopher et. al., 1989)

The internal stability requirements for a reinforced soil retaining wall requires an evaluation of: (1) the tension in the reinforcing elements, (2) the pullout resistance of the reinforcing elements, and (3) the integrity of the facing elements. The tension and pullout failure mechanisms for reinforced soil walls are illustrated in Figure 4.

The tension in the reinforcing elements can be computed from:

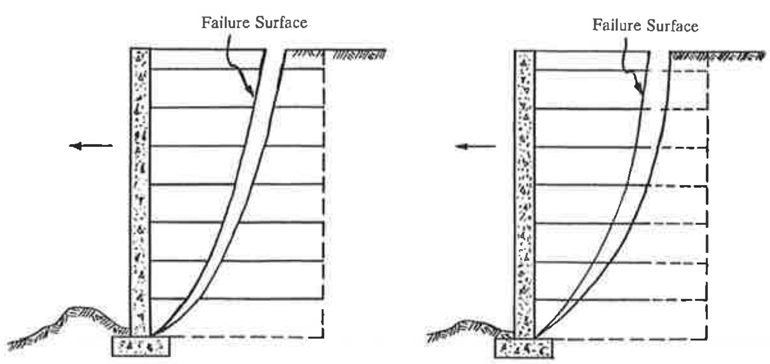
$$T = K\sigma_v(a)(w) \quad (1)$$

where: T = tension in the reinforcement
K = lateral earth pressure coefficient
σ_v = vertical soil stress
a = vertical spacing of the reinforcing elements
w = horizontal spacing of the reinforcing elements

Of course the product $K\sigma_v$ is the horizontal stress and a knowledge of this stress is essential for evaluating the tension in the reinforcement. The lateral earth pressure coefficient, K, that is used by the various soil reinforcement methods ranges from slightly greater than at-rest conditions down to the active conditions. Table 2 gives the lateral earth pressure coefficients used by the various systems that are currently available. Design envelopes of K currently used by various soil reinforce-

TABLE 2 INTERNAL DESIGN CHARACTERISTICS OF EARTH WALLS (AFTER MITCHELL AND VILLET, 1987)

Reinforcement Type	Trade Name	Failure Surface			Earth Pressure Coefficient			Durability	
		Rankine	Bilinear	Wedge with Varying Angles from Horizontal	K_a	K_o	Varying from K_o at Top of Wall to K_a at Some Depth	Reinforcement Susceptible to Corrosion	Degradation by Ultra Violet Radiation
Strip Reinforcement	Reinforced Earth		x				x	x	
	Plastics		x				x	x	
Sheet Reinforcement	Geotextiles	x				x			x
Rod Reinforcement	Soil Nailing			x	x				
	Anchored Earth			x	x			x	
Grid Reinforcement	VSL Retained Earth		x				x	x	
	MSE, GASE	x	x		x				
	Welded Wire Wall, RSE		x					x	
	Geogrid	x			x				x



(a) Tension Failure (b) Pullout Failure

FIGURE 4 Mechanisms of internal failure in reinforced soil walls.

ment systems were compiled by Christopher et al (1989) and are shown in Figure 5. These envelopes are normalized with respect to the active earth pressure coefficient, K_a of the soil. The appropriate value of K to be used in design depends on the degree of restraint that the reinforcing elements impose on the soil. The full active lateral soil pressure is appropriate for systems that allow substantial yielding in the soil to occur. As more restraint is applied to the soil, the lateral earth pressure moves toward the at-rest condition. Greater than at-rest conditions can develop in stiff systems (little lateral yielding) near the top of walls when the soil is subjected to heavy compaction in layers.

Most soil reinforcement systems recommend values of K that were determined on the bases of field measurements of tension in reinforcing elements of the system (Anderson et al, 1987; Sampaco et al, 1992; 1994). The appropriate value of K was then calculated using Equation 1 shown above. This back calculated value of K is dependent on the value of the vertical soil stress that is used. Computation of the vertical soil stress, σ_v, differs between the various reinforcement

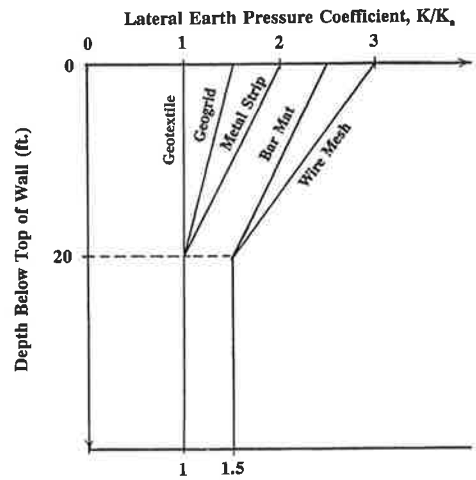


FIGURE 5 Design values of the lateral earth pressure coefficient (K) for various types of soil reinforcement systems.

systems that are available. Some design methods consider the increase in vertical stress resulting from the overturning effect within the wall; other methods simply calculate the vertical stress as a geostatic stress in level ground. Actual field observations indicate a slightly different distribution (Figure 2). It is important when comparing the values of K used by the various systems that the method of computing the vertical soil stress is taken into consideration.

The pullout resistance of reinforcing elements is generally provided by two mechanisms: (1) friction and (2) passive soil resistance (lateral bearing capacity). Both mechanisms contribute to pullout resistance but one is generally more dominant depending on the type of reinforcement elements that are used. Table 3 gives the basic aspects of reinforcement pullout performance in granular and low cohesive soils. At this time neither mechanism can be computed from theory and, therefore, the results of pullout tests in the laboratory and the field have been used to establish the parameters that are used to compute the pullout resistance (Peterson and Anderson, 1980; Nielsen and Anderson, 1984; Mitchell and Villet, 1987; Juran et al, 1988; Abdel-Motaleb and Anderson, 1990).

Table 4 summarizes the pullout design equations that are currently used by various soil reinforcement systems. Note that Reinforced Earth® and Geosynthe-

TABLE 3 BASIC ASPECTS OF REINFORCEMENT PULLOUT PERFORMANCE IN GRANULAR AND LOW COHESIVE SOILS (AFTER CHRISTOPHER ET. AL., 1989)

Reinforced Soil System	Generic Reinforcement Type	Major Load Transfer Mechanism	Displacement to Pull-out	Long Term Performance
Mechanically Stabilized Embankments	Inextensible strips	Frictional		
	smooth	L.D.	0.05 in	Noncreeping
	ribbed	H.D.	0.5 in	
	Extensible composite plastic strips	Frictional	Dependent on Reinforcement Extensibility	Dependent on Reinforcement Structure and Polymer Creep
	Extensible sheets geotextiles	Frictional (interlocking) L.D.	Dependent on Reinforcement Extensiblity (1 t0 4 in)	Dependent on Reinforcement Structure and Polymer Creep
	Inextensible grids			
	bar mats	Passive H.D.	0.5 to 0.8 in	Noncreeping
	welded wire meshes	Frictional + Passive H.D.	0.5 to 0.8 in	Noncreeping
	Extensible grids			
	geogrids	Frictional + Passive H.D.	Dependent on Extensibility (1 to 2 in)	Dependent on Reinforcement Structure and Polymer Creep
	woven meshes	Frictional + Passive H.D.	1 to 2 in	Noncreeping
	Anchors	Passive	0.2 to 0.4 in	Noncreeping
Ground Reinforcement	Nails (ground reinforcement)	Frictional H.D.	0.08 to 0.12 in	Noncreeping

Note: L.D. - low dilatancy effect H.D - high dilatancy effect 1 in = 25.4 mm

TABLE 4 PULLOUT CAPACITY DESIGNS EQUATIONS CURRENTLY USED BY VARIOUS SOIL REINFORCEMENT SYSTEMS (AFTER MITCHELL AND VILLET, 1987)

Reinforcement Type	Trade Name	Semi Empirical Equation for Pullout Capacity		
		Frictional	Passive	Frictional + Passive
Strip Reinforcement	Reinforced Earth	$P = \mu^* \gamma z L_e 2b$ $0.5 \leq \mu^* \leq 1.5$		
Sheet Reinforcement	Geotextiles	$P = \tan(2\phi/3)\gamma z L_e 2$		
Rod Reinforcement	Soil Nailing	$P = x d L_e (c + \gamma z \tan \phi)$		
	Anchored Earth		$P = (K_p \gamma z \theta t / \cos\alpha_1)\, e^{[2(3/4\pi - \alpha 1)\tan\phi]}$	
Grid Reinforcement	VSL Retained Earth		$P = A_c \gamma z d b n$ $15 \leq A_c \leq 40$	
	Welded Wire Wall, RSE Wall			$P = (663 + \gamma z d[\pi L_e M \tan\delta + 36.8n])$ for clean sands: $11^o \leq \delta \leq 22^o$
	Tensar Geogrid			$P = L_e b \gamma z[(2\alpha_s \tan\delta) + (\sigma_b' t \alpha_b)/\sigma_z S_x)]$ $5 \leq \sigma_b'/\sigma_z \leq 100$

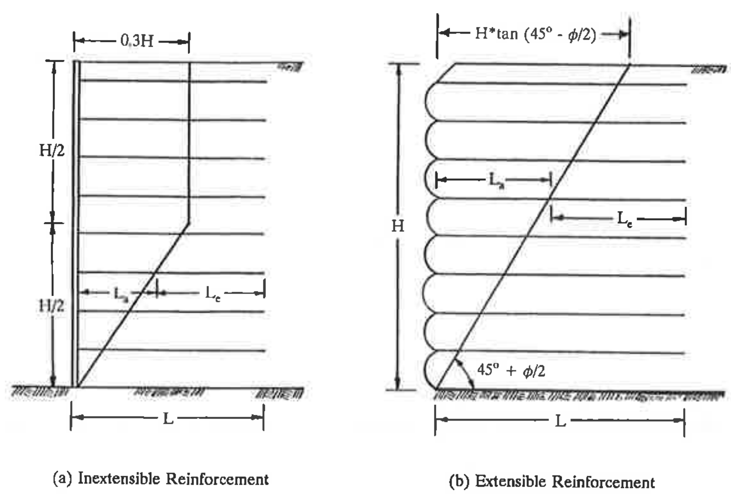


FIGURE 6 Locations of potential failure surface in reinforced soil walls.

tics use strip and sheet elements for reinforcement and therefore it is logical that friction is the mechanism responsible for providing pullout resistance. At the other end of the spectrum, Anchored Earth and the Syro Anchored Retaining Wall systems use passive resistance as the pullout resistance mechanism. Again, this is logical because these two systems use embedded anchors and the contribution from friction is obviously small. Both friction and passive resistance are available to provide pullout resistance for grid reinforcement systems. Separation of the components is difficult and the methods of pullout resistance computation is different for different available methods. VSL Retained Earth walls consider only passive resistance and the estimations are made on the basis of pullout tests. The Hilfiker Welded Wire Wall and RSE wall systems as well as the Tensar Geogrid system all use a combination of friction and passive resistance (lateral bearing capacity) in computing the pullout resistance.

Regardless of the pullout resistance mechanism that is used, the pullout resistance must be established behind some critical failure plane (Figure 6). Earlier practice assumed that the pullout resistance must be developed behind the Coulomb failure plane. However, field measurements and theoretical analysis show that the maximum tension in the reinforcing elements and hence the location of the failure plane for evaluating pullout resistance does not correspond to the Coulomb failure plane (Juran and Schlosser, 1978; Schlosser and Elias, 1978; McKittrick, 1978; Anderson et al, 1987). Figure 6 shows the location of potential failure planes that are used in evaluating the pullout resistance of inextensible and extensible reinforced soil systems.

The facing elements of reinforced soil walls are commonly provided to retain fill material at the face and to prevent slumping and erosion of steep faces. However, the success of reinforced soil walls is also highly dependent on the type of facing system used and the care with which it is designed and constructed. Although the type of facing systems is usually dictated by aesthetic requirements, anticipated deflection of the wall face may also impose further restriction on the type of facing system selected (Allen and Holtz, 1991). Current connection strength requirements are those established by AASHTO Task Force 27 (1990). The Task Force 27 guideline states that the horizontal stress used to design the connections and facing panels for MSE walls shall be equal to the maximum horizontal stress computed at each reinforcement level unless experimental results indicate differently, but in no case shall they be less than 85% of the maximum calculated stress.

Chewning and Collin (1991) conducted several geogrid connection strength tests for Modular Block earth retaining wall systems. Two design criteria were proposed, namely: (a) *serviceability criterion* - which limits the movement in the connection between the geogrid and modular block to a maximum of 0.75 inch; and (b) *limit strength criterion* - which establishes a factor of safety of 2.0 between the allowable connection strength and the peak connection strength measured in the testing. These two criteria were later used by Buttry et al (1993) to evaluate the connection strength of eight retaining wall systems using extensible geogrid reinforcements. Similar criteria were adopted by Israelsen et al (1993) for the laboratory connection strength tests of Keystone Retaining Wall units. For RSE wall systems, the stability evaluation of facing to reinforcement connection has been recently conducted by means of laboratory anchor pullout tests (Anderson et al, 1991; Ali et al, 1992) and actual measurements of anchor loads in the field (Anderson et al, 1994; Sampaco, 1994).

CONSTRUCTION METHODS AND CONTROL

Materials Handling

Because virtually all soil reinforcing materials are put out in "packages" by various companies, specific material handling instructions are generally provided with each proprietary system. In general, though, basic common sense procedures are required. Geosynthetics should be shielded from the sun's rays, though some (notably geogrids manufactured from HDPE) are much more resistant to damage from ultraviolet radiation than other geosynthetics. Geosynthetics should also be protected from extreme temperatures (generally considered from above 60 degrees centigrade and below minus 30 degrees centigrade). Steel grids, as well as other forms of steel reinforcement are more weather tolerant, but should be kept from prolonged exposure to moisture in order to minimize premature weathering (rusting). Concrete facing panels should always be handled carefully with equipment having adequate load capacity to minimize the opportunity for cracking, chipping or breaking during handling operations. A designated "lay-down yard" near the work site is usually needed to provide sufficient opportunity to handle and store materials. The need to protect geosynthetics is the strictest and can usually be best accomplished with tarps and/or temporary sheds.

Erection Procedures

The process of erecting walls and embankments with the hybrid soil reinforcing mass is comparatively similar throughout all of the proprietary systems. As with any civil construction project, the process begins with well prepared foundation. The reinforced soil mass should be established directly upon stripped undisturbed natural soil or upon engineered fill placed to a compaction standard equal to or greater than that of the reinforced soil earth fill. Construction then proceeds by placing reinforcement and engineered fill in alternating layers according to the specific design. All of the steel grid systems (except the Welded Wire Wall) have precast concrete faces which require some alignment control (as discussed below). Geosynthetics usually form wall faces and embankment sideslopes by carrying the geosynthetics around the exposed face of the earth fill layer on top, a procedure known as "wrapping around." However, precast concrete faces are frequently used as a facing alternative with Tensar geogrid reinforcement.

It is generally necessary to stake out geogrids in order to keep them in place during the initial fill placement on top of the grids. Any damaged reinforcing materials should be removed; this means that grids which have been cut should be examined carefully and those with several cuts discarded. The most serious type of cut involves longitudinal elements (those wires or strips of synthetic grid which are perpendicular to the face of the embankment or wall). These are the elements which link together the "anchoring" elements parallel to the wall face; these "anchoring" elements provide passive resistance (which is the primary source of pullout resistance) and so it is essential that they remain intact. Any torn or damaged geofabric sheets should also be removed. In no case shall construction equipment be allowed to drive directly on any reinforcing elements; fill should be placed ahead of equipment to preclude this from occurring.

Alignment Control

As noted above, precast concrete faces are commonly utilized with steel grid systems. A cast-in-place continuous concrete leveling strip or precast concrete panel sections are required to begin proper alignment control for the facing panels; this is installed along the foundation of the wall at the face to form a foundation for the panel sections. Additionally, exterior bracing of some type (usually placed in front of the wall face) is required as a temporary support for the precast panels of all systems except the Reinforced Soil Embankment. The bracing is used to maintain alignment of the panels during construction. Alignment of the Welded Wire Wall face is accomplished by initial proper layout of the foundation wall sections, with no concrete leveling strip required. Alignment of geosynthetic reinforced walls and embankments is accomplished in the same manner with the remainder of the wall being comparatively easy to align once the foundation sections are correctly laid out. Care should be taken for all systems, particularly those not allowed to work so close to the face that bulging and/or distortion occurs.

Earthwork Control

Earthwork control for all reinforced soil structures continues to be simply an exercise in engineered fill control. Special attention should always be given to thorough compaction of soil at the face of walls and embankments which do not have concrete faces; if this is not performed properly, the face will probably experience some compression settlement due to moisture from runoff and rainfall. This is not a structural problem, but the resulting aesthetics are generally considered undesirable.

Uniform compaction is also needed throughout the fill to minimize the opportunity for compression settlement in the fill mass. Such compression settlement can cause a downward drag on reinforcing elements and create additional unwanted stresses in the elements, particularly at the face with those elements attached to concrete panels.

APPLICATIONS

General

In the past ten years, the variety of applications for reinforced soil technology has grown dramatically. The increased availability, variety of systems and cost competitiveness has encouraged more frequent use, which has, in turn, provided incentive for technology to grow further. Routine applications include bridge abutments, landslide stabilizations, steep embankment sideslopes and vertical/near-vertical retaining walls. Foundation improvement for embankments founded on soft soils (C = 100 - 200 psf) is another application for geofabrics which is becoming more common. Utilization of reinforced soil technology has been successfully applied to hard rock situations; the lower part of the wall face is rock bolted and braced with walers until the wall is built up enough to establish a base width sufficient for conventional reinforced soil fill. Almost any situation requiring an abrupt change in grade (vertical or near-vertical) presents a possible application of reinforced soil technology. However, it is most applicable when new fill is placed as opposed to performing an excavation in existing soil and replacing that excavation with a reinforced soil mass (eg. a retaining wall). In this type of a "cut and fill" situation, other types of retaining systems (such as tied-back walls, cantilever walls, or soil nailing) is frequently more cost-effective.

Limitations and Advantages

The various systems developed during the past ten years (which includes steel grids, bent steel rods, geogrids and geofabrics) all have different advantages with respect to each other and with respect to the original reinforcement system utilizing steel straps, marketed by the Reinforced Earth Company. While it is more or less true that any system can be used to duplicate a structure built with another system (provided a sufficient amount of reinforcement is used), there are some inherent advantages in each which should be considered for cost competitiveness.

These advantages and disadvantages are largely concerned with the backfill used for reinforcement embedment, steepness of slope and overall constructed height, corrosion resistance and aesthetics of the finished structure. There are some other minor nuances (such as the required depth of embedment and, hence, the amount of reinforced soil fill required for construction), but these are the major areas of concern.

In general, those systems utilizing reinforcing elements which employ passive soil resistance (grids and bent steel rods) are able to tolerate a much wider range of soils for use as backfill than those which depend solely on friction for the soil-reinforcement interaction (straps and sheets of fabric). Sands and gravels with a significant fraction of low plasticity silts and clays (as much as 30% to 35 %) may be considered for such systems, whereas sands and gravels with a comparatively low fines content (15% or less) are needed for the friction-type systems. Backfill soils which are predominantly silts and clays are presently being used on a limited basis with Tensar's geogrid systems, but sufficient research and testing has not yet been completed to provide design information and confidence for general use. Soil creep is primarily the problem which must be accounted for, and it is anticipated that this will be compensated for by utilizing lower allowable pullout capacity for grids in plastic soils.

Because of the lower design strengths, as well as the "wrap around" face design, geosynthetics are more easily adapted to sloping embankments than vertical or near-vertical faced retaining walls. Although the use of geosynthetic wall systems of different wall heights have increased significantly in recent years, their widespread use is still hindered by the difficulty in assessing their long term strength (Allen and Holtz, 1991). In contrast, steel grid systems have higher design strengths and are generally faced with precast reinforced concrete panel faces and so must be vertical or near-vertical. Consequently, these systems are more easily utilized to construct retaining walls. Only by stepping back with a series of wall segments in discrete tiers can these systems be used to construct an embankment with an overall sideslope flatter than a near-vertical face created with the precast concrete panel facing. If this stepping is done, additional costs in capping courses and base course alignment courses are incurred for each wall segment.

One of the most difficult problems which has faced the developers of all of the steel reinforcing systems is that of corrosion resistance, and hence project life. With the advent of polymer geogrids and geosynthetics, a major step forward in dealing with this problem was taken. Both materials provide very effective reinforcement which can be used in high corrosion situations, from seawalls to causeway embankments to highway embankments subject to frequent application of corrosive de-icing salts. Durability of polymer geogrids and geosynthetics in any highly corrosive situation is generally superior to steel reinforcing systems. Developers of steel reinforcing systems have experimented with double-dip galvanizing and epoxy coatings, as well as providing sacrificial anodes in the fill. In general these approaches are more uncertain and more expensive than polymer geogrids, unless the structural requirements are such that the higher design strengths of the steel are needed. If this is the case, providing extra steel thickness for sacrificial purposes rather than using any coatings or additional galvanizing is the approach which should be considered for simplicity and ease of quality control.

As noted, aesthetics is also an important factor. Precast concrete panel faces are generally "neat" and "clean" in appearance but are more expensive than a Welded Wire Wall face or a geosynthetic wrap-around face. A geosynthetic wrap-around face can be covered by planting the face utilizing specialized mats to retain the top soil until the plantings have an opportunity to take root. The Welded Wire Wall face can be covered with wood, a concrete cast-in-place face or gunite, depending on the desired finish. In addition, most companies offer a wide variety of finishes for the precast concrete panels, including exposed aggregate, colored panels, and other different textures. In general, an enormous amount of versatility is afforded to the potential user of reinforced soil technology, with respect to the aesthetics of the final finished product, however, costs increase substantially with each "refinement". Therefore, the desired aesthetics should be balanced against project costs.

A SUCCESSFUL PROJECT

The successful use of a mechanically stabilized earth (M.S.E.) structure begins with an evaluation of the application, includes development of design data and review of structure designs and continues through construction inspection. Prior to initiating the design process, a thorough evaluation of the application for which an M.S.E. structure has been proposed should be completed. Such an evaluation requires a knowledge of how M.S.E. structures function, how they are constructed and what factors control the cost-effectiveness of their use. All evaluations should at least consider the following:

- Architectural Requirements
- Availability Of Suitable Backfill
- Construction Access
- Contractor Expertise
- Corrosion
- Excavation Restrictions
- External Loadings
- Foundation Conditions
- Geometric Constraints
  - Alignment
  - Obstructions to Soil Reinforcements
  - Penetrations
- Quantity and Height of Structure

Any one or more of the factors listed above may cause the use of an M.S.E. structure to be impractical or cost prohibitive and thereby requiring other construction methods. Assuming the proposed application is found to be suitable, design data must then be developed for use in preparing structure designs. In general, actual structure designs will be provided by the suppliers of the proprietary systems, as determined to be eligible for use in the project. The data must be complete enough such that proprietary designs can be prepared and included in the project construction documents or used by contractors as a basis for bidding.

The data prepared for use during the design process should address the following:

- Geometrics
  - Horizontal Alignment
  - Existing and Proposed Profiles
  - Beginning and Ending Stations
  - Design Tolerances
  - Excavation Restrictions
- Foundation Conditions
  - Allowable Bearing Capacities
  - Resistance to Sliding
  - Minimum Embedment Depths
  - Differential and Total Settlements
- Structure Backfill
  - Unit Weight
  - Internal Friction Angle
  - Cohesion
  - Plasticity Index (P.I.)
  - Gradation
  - Electrochemical Properties
- Surface and Subsurface Drainage
- External Loads
  - Soil Loads or Data for Determining Surcharge Conditions
  - Live Loads
  - Structure or Other Special Loadings
- Design Criteria
  - Minimum Factors of Safety for Sliding, Overturning, Bearing Capacity and Pullout
  - Allowable Tensile Stresses
  - Required Service Life
  - Minimum Soil Reinforcement Lengths or Ratios
  - Alignment Tolerances
- Seismic Requirements
  - Seismic Accelerations
  - Reduction in Factors of Safety
  - Increase in Allowable Tensile Stresses
  - Permissible Yielding or Deformation
- Architectural Treatments
  - Facing Requirements
  - Battered or Stepped Faces
  - Landscaping/Planting Requirements
  - Coloring
- Utility Information
  - Existing and Proposed Pipelines
  - Underground Cabling
  - Drainage Structures
  - Overhead Lighting, Signage or Power
  - Facing Penetrations
- Submittal Requirements
  - Plan Format
  - Plan Views
  - Elevation (Profile) Views
  - Sections
  - Details
  - Quantities
  - Specifications
  - Design Calculations
  - Materials Testing/Certifications
- Special Requirements
  - Instrumentation (if required)
  - Pullout Testing (if required)
  - Technical Assistance
  - Contractor Knowledge

If proprietary designs are to be included in the project construction documents, the design data should be provided to eligible suppliers well in advance to allow time for design, review, response to review comments and integration into the project documents. Depending upon the complexity or magnitude of the proposed structure(s) an on-site predesign meeting may be required for all interested suppliers. During the design process, the project engineer's responsibility is to disseminate the design data to interested suppliers, review and approve design submittals and coordinate the assemblage of the construction documents. Each proprietary design should be checked for compliance with the design data, accuracy, consistency with other designs, treatment of special details, and verification of indicated quantities.

If proprietary designs are not required for the construction documents, a generic design should be prepared by the project engineer (or agency) and included in the project design package. The design should graphically illustrate structure geometrics in both plan and elevation views, cross sections and special details and provide quantities upon which bids are to be based. The project special provisions should contain a list of all M.S.E. structure systems which are considered acceptable for the project. In addition, the balance of the design data should be made available during the bid process to eligible proprietary systems for their use in preparing bids. Following the selection of the successful contractor and identification of the system to be used, a detailed design submittal will be required.

In preparation for construction, a preconstruction conference should be held and attended by the technical representative of the selected M.S.E. Structure system. Specific issues relating to M.S.E. Structures that should be addressed include:

- Technical Assistance
- Backfill Sources
- Materials Testing/Inspection
    - Backfill (Strength & Electrochemical)
    - Concrete Facings (if required)
    - Manufacturer's Certifications
    - Compaction
- Foundation Preparation
- Compaction Requirements and Techniques
- Drainage Control
- Scheduling

Nearly all proprietary suppliers provide some form of M.S.E. construction guide which outlines step-by-step erection procedures and recommended practices. In addition, technical assistance is available from the suppliers to periodically assist the contractor during construction. However, it is the project engineer's responsibility to ensure that the M.S.E. structure(s) is constructed in conformance with the plans and specifications.

The project engineer's inspection of the M.S.E. Structure(s) construction must address the plans and specifications; materials inspection; and structure erection. The inspector must be familiar with the plans and specifications for the selected M.S.E. system and the proprietary suppliers construction guide. The primary goal of the inspector should be to assure that the contractor provides a completed M.S.E. structure(s) which is within the specifications and meets the conditions for which it was designed.

Components to be inspected prior to installation in an M.S.E. structure include:

- Soil Reinforcements
- Facing Elements
- Bearing Pads & Joint Fillers (if required)
- Structure Backfill

Acceptance or rejection of components should be based on a combination of material testing, certification and physical inspections. Adequate backfill is critical to the proper performance of an M.S.E. structure(s). As such the inspector must ensure that the backfill not only conforms to the requirements of the specifications, but is also properly placed.

During erection of the M.S.E. structure(s) the inspector should address the following:

- Alignment Tolerances
- Temporary Excavations
- Foundation Preparation
- Installation of Subsurface Drain (if required)
- Leveling Pad Placement (if required)
- Placement of Facing Elements
- Backfill Placement and Compaction
- Control of Surface Drainage

In summary, if the proposed M.S.E. structure application is appropriate, sufficient design data are generated, proprietary designs are thoroughly reviewed, and a comprehensive construction inspection program is provided, the completed M.S.E. structure will successfully function under the conditions for which it was designed, while providing significant reductions in cost over other methods of construction.

ACKNOWLEDGMENT

In preparation of this Circular valuable information was provided by Jerold A. Bishop and other members of the ASCE Technical Committee on Soil Improvement and Geosynthetics and their contributions are gratefully acknowledged.

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