GEOSYNTHETICS FOR SOIL REINFORCEMENT

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By

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GEOSYNTHETICS FOR SOIL REINFORCEMENT

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Abstract: This lecture introduces geosynthetic materials and briefly describes their types and manufacture, functions and applications, properties and tests, design, selection, and specifications. Geosynthetics for soil reinforcement are then discussed in some detail, with specific applications to embankments on soft foundations, steep slopes, and for the backfills of retaining walls and abutments. Emphasis is on the materials properties of the geosynthetics required for design and construction.

1. INTRODUCTION

Historically, major developments in structural engineering have only been possible because of parallel developments in the technology of construction materials. Larger and more elaborate structures became possible as we went from using wood to building stone to concrete to reinforced concrete and most recently to prestressed reinforced concrete. The development of steel enabled the construction of longer span bridges and taller buildings than were possible using wrought iron or other traditional construction materials. Because the materials of geotechnical engineering are soil and rock, it is difficult to think of similar parallel developments in geotechnical construction and earthen materials in our field. Compaction and other soil improvement techniques occurred largely because of developments in construction equipment by manufacturers and contractors. Probably the best example of a parallel development between material and the construction application is soil reinforcement. In a direct analogy with reinforced concrete, steel and polymeric materials provide tensile resistance and stability to soils that have low to no tensile strength.

Polymeric reinforcement materials are a subset of a much larger recent development in civil engineering materials: *geosynthetics*. Geosynthetics are planar products manufactured from polymeric materials (the *synthetic*) used with soil, rock, or other geotechnical-related material (the *geo*) as part of a civil engineering project or system. There are few developments that have had such a rapid growth and strong influence on so many aspects of civil engineering practice as geosynthetics. In 1970, there were only five or six geosynthetics available, while today more than 600 different geosynthetic products are sold throughout the world. The size of the market, both in terms of square meters produced and their value, is indicative of their influence. Worldwide annual consumption of geosynthetics is close to 1000 million m^2, and the value of these materials is probably close to US$1500 million. Since the total cost of the construction is at least four or five times the cost of the geosynthetic itself, the impact of these materials on civil engineering construction is very large indeed.

In less than 30 yr, geosynthetics have revolutionized many aspects of our practice, and in some applications they have entirely replaced the traditional construction material. In many cases, the use of a geosynthetic can significantly increase the safety factor, improve performance, and reduce costs in comparison with conventional design and construction alternates.

The first part of this paper is an introduction to geosynthetic materials; included are brief descriptions of their types and manufacture, functions and applications, properties and tests, design, selection, and specifications. The second part deals with the use of geosynthetics for soil reinforcement, with specific applications to embankments on soft foundations, steep slopes, and retaining walls and abutments.

2. DEFINITIONS, TYPES, MANUFACTURE, AND IDENTIFICATION

2.1. Definitions and Types

ASTM has defined a *geosynthetic* as a planar product manufactured from a polymeric material used with soil, rock, earth, or other geotechnical-related material as an integral part of a civil engineering project, structure, or system. A *geotextile* is a permeable geosynthetic made of textile materials. *Geogrids* are primarily used for reinforcement; they are formed by a regular network of tensile elements with apertures of sufficient size to interlock with surrounding fill material. *Geomembranes* are low-permeability geosynthetics used as fluid barriers. Geotextiles and related products such as nets and grids can be combined with geomembranes and other synthetics to take advantage of the best attributes of each component. These products are called *geocomposites,* and they may be composites of geotextile-geonets, geotextile-geogrids, geotextile-geomembranes, geomembrane-geonets, geotextile-polymeric cores, and even three-dimensional polymeric cell structures. There is almost no limit to the variety of geocomposites that are possible and useful. The general generic term encompassing all these materials is *geosynthetic*. A convenient classification system for geosynthetics is given in Fig. 1.

2.2. Types and Manufacture

Most geosynthetics are made from synthetic polymers such as polypropylene, polyester, polyethylene, polyamide, PVC, etc. These materials are highly resistant to biological and chemical degradation. Natural fibers such as cotton, jute, bamboo, etc., could be used as geotextiles and geogrids, especially for temporary applications, but with few exceptions they have not been promoted or researched as widely as polymeric geosynthetics.

In manufacturing geotextiles, elements such as fibers or yarns are combined into planar textile structures. The fibers can be continuous *filaments,* which are very long thin strands of a polymer, or *staple fibers,* which are short filaments, typically 20 to 100 mm long. The fibers may also be produced by slitting an extruded plastic sheet or film to form thin flat tapes. In both filaments and slit films, the extrusion or drawing process elongates the polymers in the direction of the draw and increases the fiber strength.

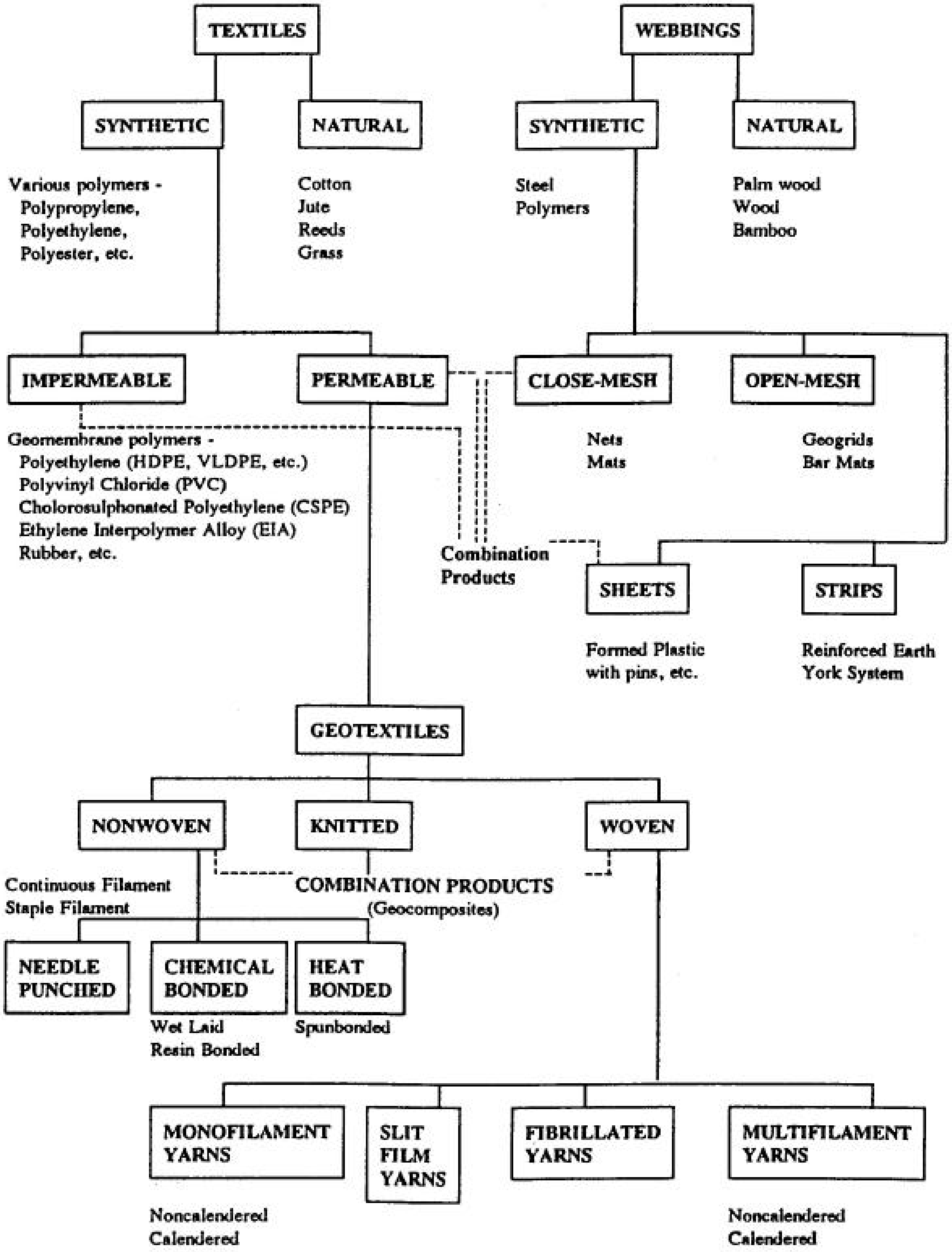

Fig. 1. Classification of geosynthetics and other soil inclusions.

Geotextile type is determined by the method used to combine the filaments or tapes into the planar textile structure. The vast majority of geotextiles are either *woven* or *nonwoven.* Woven geotextiles are made of *monofilament, multifilament,* or *fibrillated* yarns, or of slit films and tapes. Although the weaving process is very old, nonwoven textile manufacture is a modem industrial development. Synthetic polymer fibers or filaments are continuously extruded and spun, blown or otherwise laid onto a moving belt. Then the mass of filaments or fibers are either *needlepunched,* in which the filaments are mechanically entangled by a series of small needles, or *heat bonded,* in which the fibers are *welded* together by heat and/or pressure at their points of contact in the nonwoven mass.

Stiff geogrids with integral junctions are manufactured by extruding and orienting sheets of polyolefins. Flexible geogrids are made of polyester yarns joined at the crossover points by knitting or weaving, and coated with a polymer.

For additional details on the composition, materials, and manufacturing of geosynthetics, see Koerner (1998).

2.3. Identification

Geosynthetics are generically identified by: (1) polymer; (2) type of fiber or yarn, if appropriate; (3) type of geosynthetic; (4) mass per unit area or thickness, if appropriate; and (5) any additional information or physical properties necessary to describe the material. Four examples are:

- polypropylene staple fiber needlepunched nonwoven, 350 g/m^2;
- polyethylene net, 440 g/m^2 with 8 mm openings;
- polypropylene biaxial geogrid with 25 mm x 25 mm openings; and
- high-density polyethylene geomembrane, 1.5 mm thick.

3. FUNCTIONS AND APPLICATIONS

Geosynthetics have six primary functions:

1. filtration
2. drainage
3. separation
4. reinforcement
5. fluid barrier, and
6. protection

Geosynthetic applications are usually defined by their primary, or principal, function. In a number of applications, in addition to the primary function, geosynthetics usually perform one or more secondary functions. It is important to consider both the primary and secondary functions in the design computations and specifications.

More than 150 separate applications of geosynthetics have been identified (Holtz et al., 1997; Koerner, 1998). A few examples follow:

Geotextile filters replace graded granular filters in trench drains to prevent soils from migrating into drainage aggregate or pipes. They are also used as filters below riprap and other armor materials in coastal and river bank protection systems. Geotextiles and geocomposites can also be used as drains, by allowing water to drain from or through soils of lower permeability. Examples include pavement edge drains, slope interceptor drains, and abutments and retaining wall drains.

Geotextiles are often used as separators to prevent fine-grained subgrade soils from being pumped into permeable, granular road bases and to prevent road base materials from penetrating into the underlying soft subgrade. Separators maintain the design thickness and roadway integrity.

Geogrid and geotextile reinforcement enables embankments to be constructed over very soft foundations. They are also used to construct stable slopes at much steeper angles than would otherwise be possible. Polymeric reinforced backfills for retaining walls and abutments was mentioned in the Introduction.

Geomembranes, thin-film geotextile composites, geosynthetic-clay liners, and field-coated geotextiles are used as fluid barriers to impede the flow of a liquid or gas from one location to another. This geosynthetic function has application in asphalt pavement overlays, encapsulation of swelling soils, and waste containment. In the sixth function, protection, the geosynthetic acts as a stress relief layer. A protective cushion of nonwoven geotextiles is often used to prevent puncture of geomembranes (by reducing point stresses) from stones in the adjacent soil or drainage aggregate during installation and while in service.

4. DESIGN AND SELECTION

In the early days where there were only a few geotextiles available, design was mostly by trial and error and product selection was primarily by type or brand name. Today, however, with such a wide variety of geosynthetics available, this approach is inappropriate. The recommended approach for designing, selecting, and specifying geosynthetics is no different than what is commonly practiced in any geotechnical engineering design. First, the design should be made without geosynthetics to see if they really are needed. If conventional solutions are impractical or uneconomical, then design calculations using reasonable engineering estimates of the required geosynthetic properties are carried out. Next, generic or performance type specifications are written so that the most appropriate and economical geosynthetic is selected, consistent with the properties required for its design functions, ability to survive construction, and its durability. In addition to conventional soils and materials testing, testing and properties evaluation of the geosynthetic is necessary. Finally, as with any other construction, design with geosynthetics is not complete until construction has been satisfactorily carried out. Therefore, careful field inspection during construction is essential for a successful project. Additional discussion on all these points is given by Holtz et al. (1997).

5. GEOSYNTHETICS PROPERTIES AND TESTS

5.1. Introduction

Because of the wide variety of products available, with different polymers, filaments, weaving patterns or bonding mechanisms, thickness, mass, etc., geosynthetics have a considerable range of physical and mechanical properties. A further complicating factor is the variability of some properties, even within the same manufactured lot or roll; also, some differences may be due to the test procedures themselves.

Thus, determination of the design properties is not necessarily easy, although geosynthetic testing has progressed significantly in the past 20 yr. Standard procedures for testing geosynthetics have been developed by ASTM and other standards development organizations throughout the world, particularly in Europe, Japan, and Australia. The design properties required for a design will depend on the specific application and the associated function(s) the geosynthetic is supposed to provide.

Geosynthetic properties can be classified as (1) general, (2) index, and (3) performance properties. See Holtz et al. (1997) for a listing of the various properties under these categories, while Koerner and Hsuan (2001) describe test methods for the various geosynthetics properties, including those appropriate for geomembranes and other products used for waste containment.

5.2. General and Index Properties and Tests

General properties include the polymer, mass per unit area, thickness, roll dimensions and weight, specific gravity, etc. Index tests do not give an actual design property in most cases, but they do provide a qualitative assessment of the property of interest. When determined using standard test procedures, index test values can be used for product comparison, specifications, quality control purposes, and as an indicator of how the product might survive the construction process. These latter properties are called constructability or survivability properties. Index tests include uniaxial mechanical strength (grab tensile; load-strain; creep, tear, and seam strength); multiaxial rupture strength (puncture, burst, and cutting resistance; flexibility); endurance or durability tests (abrasion resistance; UV stability; chemical and biological resistance; wet-dry and temperature stability); and hydraulic index tests (apparent opening size, percent open area; pore size distribution; porosity; permeability and permittivity; transmissivity).

5.3. Performance Properties and Tests

Performance properties require testing the geosynthetic and the soil together in order to obtain a direct assessment of the property of interest. Because performance tests should be conducted under design specific conditions and with soil samples from the site, these tests must be performed under the direction of the design engineer. Performance tests are not normally used in specifications; rather, geosynthetics should be preselected for performance testing based on index values, or performance test results should be correlated to index values for use in specifications. Examples of performance tests include in-soil stress-strain, creep, friction/adhesion, and dynamic tests; puncture; chemical resistance; and filtration or clogging resistance tests.

6. SPECIFICATIONS

Good specifications are essential for the success of any civil engineering project, and this is especially true for projects in which geosynthetics are to be used. Christopher and DiMaggio (1984) and Holtz et al. (1997) give guidance on writing generic and performance-based geotextile specifications. Specifications should be based on the specific geosynthetic properties required for design, installation, and long-term performance. To specify a particular brand name of a geosynthetic or its equivalent can cause difficulties during installation. The contractor may select a product that has completely different properties than intended by the designer, and determination of what is "equivalent" is always a problem.

All geosynthetic specifications should include:

- general requirements
- specific geosynthetic properties
- seams and overlaps
- placement procedures
- repairs, and
- acceptance and rejection criteria

General requirements include the types of geosynthetics, acceptable polymeric materials, and comments related to the stability of the material. Geosynthetic manufacturers and representatives are good sources of information on these characteristics. Other items that should be specified in this section are instructions on storage and handling so products can be protected from exposure to ultraviolet light, dust, mud, or anything that may affect its performance. If pertinent, roll weight and dimensions may also be specified, and certification requirements should be included in this section.

Specific geosynthetic physical, index, and performance properties as required by the design must be listed. Properties should be given in terms of minimum (or maximum) average roll values (MARV) and the required test methods. MARVs are the smallest (or largest) anticipated average value that would be obtained for any roll tested (Holtz et al. 1997; Koerner, 1998). This average property value must exceed the minimum (or be less than the maximum) value specified for that property based on a particular test. Ordinarily it is possible to obtain a manufacturer's certification for MARVs.

Approved products lists can also be developed based on laboratory testing and experience with specific applications and conditions. Once an approved list has been established by an agency, new geosynthetics can be added after appropriate evaluation. Development of an approved list takes considerable initial effort, but once established, it provides a simple and convenient method of specifying geosynthetics.

In virtually all geosynthetics applications, seams or overlaps are required and must be clearly specified. A minimum overlap of 0.3 m is recommended for all geotextile applications, but overlaps may be increased due to specific site and construction requirements. If overlaps will not work, then the geosynthetics must be seamed. Geotextiles are commonly seamed by sewing; see Holtz et al. (1997) for details. The specified seam strengths should equal the required strength of the geosynthetic, in the direction perpendicular to the seam length and using the same test procedures. Seam strengths should not be specified as a percent of the geosynthetic strength. Geogrids and geonets may be connected by mechanical fasteners, though the connection may be either structural or a construction aid (i.e., strength perpendicular to the seam length is not required by design). Geomembranes are thermally or chemically bonded; see Koerner (1998) for details.

For sewn geotextiles, geomembranes, and structurally connected geogrids, the seaming material (thread, extrudate, or fastener) should consist of polymeric materials that have the same or greater durability as the geosynthetic being seamed. This is true for both factory and field seams.

Placement procedures should be specified in detail and on the construction drawings. These procedures include grading and ground-clearing requirements, aggregate specifications, aggregate lift thickness, and equipment requirements. These requirements are especially important if the geosynthetic was selected on the basis of survivability. Detailed placement procedures are given by Holtz et al. (1997).

Repair procedures for damaged sections of geosynthetics (i.e., rips and tears) should be detailed in the specifications.

Geosynthetic acceptance and rejection criteria should be clearly and concisely stated in the specifications. All installations should be observed by a competent inspector who is knowledgeable about placement procedures and design requirements. Sampling and testing requirements should also be specified.

7. GEOSYNTHETICS FOR SOIL REINFORCEMENT

The three primary applications soil reinforcement using geosynthetics are (1) reinforcing the base of embankments constructed on very soft foundations, (2) increasing the stability and steepness of slopes, and (3) reducing the earth pressures behind retaining walls and abutments. In the first two applications, geosynthetics permit construction that otherwise would be cost prohibitive or technically not feasible. In the case of retaining walls, significant cost savings are possible in comparison with conventional retaining wall construction. Other reinforcement and stabilization applications in which geosynthetics have also proven to be very effective include roads and railroads, large area stabilization, and natural slope reinforcement, but these applications are not discussed in this paper.

8. REINFORCED EMBANKMENTS ON SOFT FOUNDATIONS

8.1. Concept

The design and construction of embankments on soft foundation soils is a very challenging geotechnical problem. As noted by Leroueil and Rowe (2001), successful projects require a thorough subsurface investigation, properties determination, and settlement and stability analyses. If the settlements are too large or instability is likely, then some type of foundation soil improvement is warranted. Traditional soil improvement methods include preloading/surcharging with drains; lightweight fill; excavation and replacement; deep soil mixing, embankment piles, etc., as discussed by Holtz (1989) and Holtz et al. (2001a). Today, geosynthetic reinforcement must also be considered as a feasible treatment alternative. In some situations, the most economical final design may be some combination of a traditional foundation treatment alternative together with geosynthetic reinforcement. Figure 2a shows the basic concept for using geosynthetic reinforcement. Note that the reinforcement will not reduce the magnitude of long-term consolidation or secondary settlement of the embankment.

8.2. Design Considerations

As with ordinary embankments on soft soils, the basic design approach for reinforced embankments is to design against failure. The ways in which embankments constructed on soft foundations can fail have been described by Terzaghi et al. (1996),

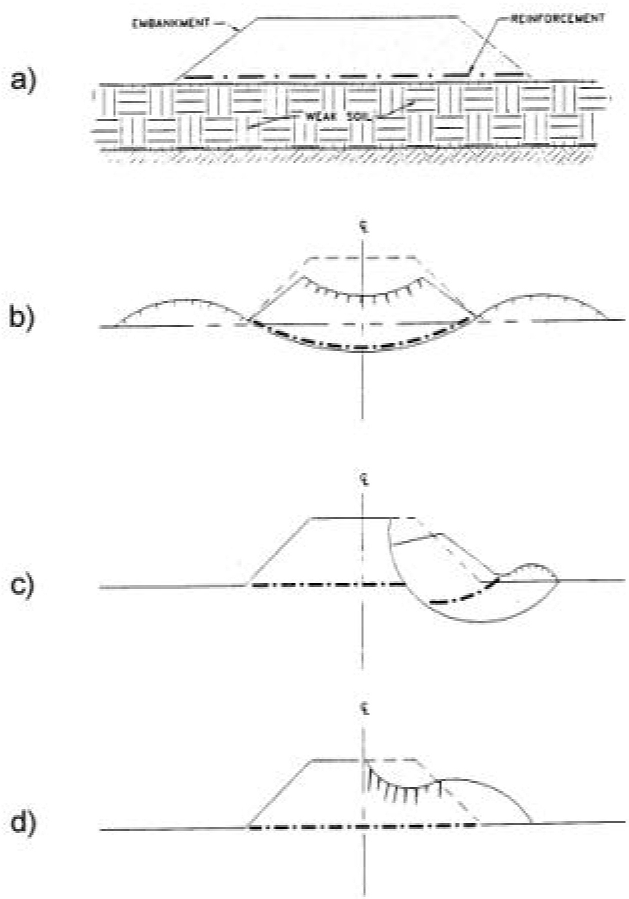

Fig. 2. Reinforced embankments: a) concept; b) bearing failure; c) rotational failure; and d) lateral spreading.

among others. Figure 2 b-d shows unsatisfactory behavior that can occur in reinforced embankments. The three possible modes of failure indicate the types of stability analyses that are required for design. Overall bearing capacity of the embankment must be adequate, and the reinforcement should be strong enough to prevent rotational failures at the edge of the embankment. Lateral spreading failures can be prevented by the development of adequate shearing resistance between the base of the embankment and the reinforcement. In addition, an analysis to limit geosynthetic deformations must be performed. Finally, the geosynthetic strength requirements in the longitudinal direction, typically the transverse seam strength, must be determined.

Discussion of these design concepts as well as detailed design procedures are given by Christopher and Holtz (1985), Bonaparte et al. (1987), Holtz (1989 and 1990), Humphrey and Rowe (1991), Holtz et al. (1997), and Leroueil and Rowe (2001).

The calculations required for stability and settlement utilize conventional geotechnical design procedures modified only for the presence of the reinforcement. Because the most critical condition for embankment stability is at the end of construction, the total stress method of analysis is usually performed, which is conservative since the analysis generally assumes that no strength gain occurs in the foundation soil. It is always possible of course to calculate stability in terms of effective stresses provided that effective stress shear strength parameters are available and an accurate estimate of the field pore pressures can be made during the project design phase. Because the prediction of in situ pore pressures in advance of construction is not easy, it is essential that the foundation be instrumented with high quality piezometers during construction to control the rate of embankment filling. Preloading and staged embankment construction are discussed in detail by Ladd (1991) and summarized by Leroueil and Rowe (2001).

8.3. Material Properties

Based on the stability calculations, the minimum geosynthetic strengths required for stability at an appropriate factor of safety can be determined. In addition to its tensile and frictional properties, drainage requirements, construction conditions, and environmental factors must also be considered. Geosynthetic properties required for reinforcement applications are given in Table 1.

Table 1. Geosynthetic properties required for reinforcement applications.

CRITERIA AND PARAMETER	PROPERTY
Design requirements:	
a. Mechanical	
Tensile strength and modulus	Wide width strength and modulus
Seam strength	Wide width strength
Tension creep	Tension creep
Soil-geosynthetic friction	Soil-geosynthetic friction angle
b. Hydraulic	
Piping resistance	Apparent opening size
Permeability	Permeability
Constructability requirements:	
Tensile strength	Grab strength
Puncture resistance	Puncture resistance
Tear resistance	Trapezoidal tear strength
Durability:	
UV stability (if exposed)	UV resistance
Chemical and biological (if required)	Chemical and biological resistance

When properly designed and selected, high-strength geotextiles or geogrids can provide adequate embankment reinforcement. Both materials can be used equally well, provided they have the requisite design properties. There are some differences in how they are installed, especially with respect to seaming and field workability. Also, at some very soft sites, especially where there is no root mat or vegetative layer, geogrids may require a lightweight geotextile separator to provide filtration and prevent contamination of the embankment fill. However, a geotextile separator is not required if the fill can adequately filter the foundation soil.

A detailed discussion of geosynthetic properties and specifications is given by Holtz et al. (1997) and Koerner and Hsuan (2001), so only a few additional comments are given below.

The selection of appropriate fill materials is also an important aspect of the design. When possible, granular fill is preferred, especially for the first few lifts above the geosynthetic.

8.3.1. Environmental Considerations

For most embankment reinforcement situations, geosynthetics have a high resistance to chemical and biological attack; therefore, chemical and biological compatibility is usually not a concern. However, in unusual situations such as very low *(i.e.,* < 3) or very high *(i.e.,* > 9) pH soils, or other unusual chemical environments (for example, in industrial areas or near mine or other waste dumps), chemical compatibility with the polymer(s) in the geosynthetic should be checked. It is important to assure it will retain the design strength at least until the underlying subsoil is strong enough to support the structure without reinforcement.

8.3.2. Constructability (Survivability) Requirements

In addition to the design strength requirements, the geotextile or geogrid must also have sufficient strength to survive construction. If the geosynthetic is ripped, punctured, torn or otherwise damaged during construction, its strength will be reduced and failure could result. Constructability property requirements are listed in Table 1. (These are also called survivability requirements.)

See Christopher and Holtz (1985) and Holtz et al. (1997) for specific property requirements for reinforced embankment construction with varying subgrade conditions, construction equipment, and lift thicknesses. For all critical applications, high to very high survivability geotextiles and geogrids are recommended.

8.3.3. Stiffness and Workability

For extremely soft soil conditions, geosynthetic stiffness or workability may be an important consideration. The workability of a geosynthetic is its ability to support workpersons during initial placement and seaming operations and to support construction equipment during the first lift placement. Workability is generally related to geosynthetic stiffness; however, stiffness evaluation techniques and correlations with field workability are very poor (Tan, 1990). See Holtz et al. (1997) for recommendations on stiffness.

8.4. Construction

The importance of proper construction procedures for geosynthetic reinforced embankments cannot be overemphasized. A specific construction sequence is usually required in order to avoid failures during construction. Appropriate site preparation, low ground pressure equipment, small initial lift thicknesses, and partially loaded hauling vehicles may be required. Clean granular fill is recommended especially for the first few construction lifts, and proper fill placement, spreading, and compaction procedures are very important. A detailed discussion of construction procedures for reinforced embankments on very soft foundations is given by Christopher and Holtz (1985) and Holtz et al. (1997).

It should be noted that all geosynthetic seams must be positively joined. For geotextiles, this means sewing; for geogrids, some type of positive clamping arrangement must be used. Careful inspection is essential, as the seams are the “weak link” in the system, and seam failures are common in improperly constructed embankments. Finally, soft ground construction projects usually require geotechnical instrumentation for proper control of construction and fill placement; see Holtz (1989) and Holtz et al. (2001a) for recommendations.

9. REINFORCED STEEP SLOPES

9.1. Concept

The first use of geosynthetics for the stabilization of steep slopes was for the reinstatement of failed slopes. Cost savings resulted because the slide debris could be reused in the repaired slope (together with geosynthetic reinforcement), rather than importing select materials to reconstruct the slope. Even if foundation conditions are satisfactory, costs of fill and right-of-way plus other considerations may require a steeper slope than is stable in compacted embankment soils without reinforcement. As shown in Fig.3, multiple layers of geogrids or geotextiles may be placed in a fill slope during construction or reconstruction to reinforce the soil and provide increased slope stability. Most steep slope reinforcement projects are for the construction of new embankments, alternatives to retaining walls, widening of existing embankments, and repair of failed slopes.

Another use of geosynthetics in slopes is for compaction aids (Fig. 3). In this application, narrow geosynthetic strips, 1 to 2 m wide, are placed at the edge of the fill slope to provide increased lateral confinement at the slope face, and therefore increased compacted density over that normally achieved. Even modest amounts of reinforcement in compacted slopes have been found to prevent sloughing and reduce slope erosion. In some cases, thick nonwoven geotextiles with in-plane drainage capabilities allow for rapid pore pressure dissipation in compacted cohesive fill soils.

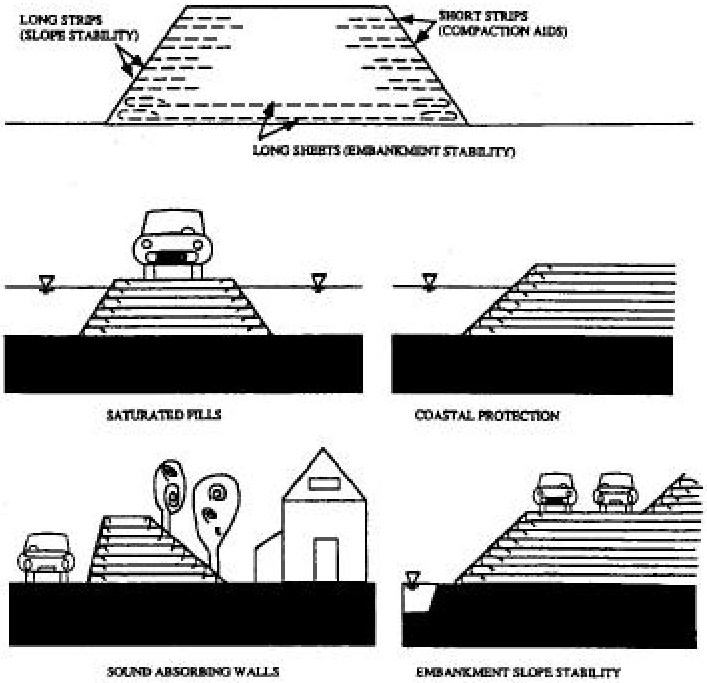

Fig. 3. Examples of multilayer geosynthetic slope reinforcement.

9.2. Design Considerations

The overall design requirements for reinforced slopes are similar to those for unreinforced slopes--the factor of safety must be adequate for both the short- and long-term conditions and for all possible modes of failure. These include: (1) internal--where the failure plane passes through the reinforcing elements; (2) external--where the failure surface passes behind and underneath the reinforced mass; and (3) compound--where the failure surface passes behind and through the reinforced soil mass.

Reinforced slopes are analyzed using modified versions of classical limit equilibrium slope stability methods (e.g., Terzaghi et al., 1996). Potential circular or wedge-type failure surfaces are assumed, and the relationship between driving and resisting forces or moments determines the factor of safety. Based on their tensile capacity and orientation, reinforcement layers intersecting the potential failure surface increase the resisting moment or force. The tensile capacity of a reinforcement layer is the minimum of its allowable pullout resistance behind, or in front of, the potential failure surface and/or its long-term design tensile strength, whichever is smaller. A variety of potential failure surfaces must be considered, including deep-seated surfaces through or behind the reinforced zone, and the critical surface requiring the maximum amount reinforcement determines the slope factor of safety.

The reinforcement layout and spacing may be varied to achieve an optimum design. Computer programs are available for reinforced slope design which include searching routines to help locate critical surfaces and appropriate consideration of reinforcement strength and pullout capacity.

Additional information on reinforced slope design is available in Christopher et al. (1990), Christopher and Leshchinsky (1991), Berg (1993), Holtz et al.(1997), and Bathurst and Jones (2001).

For slide repair applications, it is very important that the cause of original failure is addressed in order to insure that the new reinforced soil slope will not have the same problems. Particular attention must be paid to drainage. In natural soil slopes, it is also necessary to identify any weak seams that could affect stability.

9.3. Material Properties

Geosynthetic properties required for reinforced slopes are similar to those listed in Table 1, Section 8.3. Properties are required for design (stability), constructability, and durability. Allowable tensile strength and soil-geosynthetic friction are most important for stability design. Because of uncertainties in creep strength, chemical and biological degradation effects, installation damage, and joints and connections, a partial factor or reduction factor concept is recommended. The ultimate wide width strength is reduced for these various factors, and the reduction depends on how much information is available about the geosynthetics at the time of design and selection. Berg (1993), Holtz et al. (1997), and Koerner and Hsuan (2001) give details about the determination of the allowable geosynthetic tensile strength. They also describe how soil-geosynthetic friction is measured or estimated.

An inherent advantage of geosynthetic reinforcement is their longevity, especially in normal soil environments. Recent studies have indicated that the anticipated half-life of reinforfcement geosynthetics in between 500 and 5000 years, although strength characteristics may have to be adjusted to account for potential degradation in the specific environmental conditions.

Any soil suitable for embankment construction can be used in a reinforced slope system. From a reinforcement point of view alone, even lower-quality soil than conventionally used in unreinforced slope construction may be used. However, higher-quality materials offer less durability concerns, are easier to place and compact, which tends to speed up construction, and they have fewer problems with drainage. See Berg (1993) and Holtz et al. (1997) for discussion of soil gradation, compaction, unit weight, shear strength, and chemical composition.

9.4. Construction

Similarly to reinforced embankments, proper construction is very important to insure adequate performance of a reinforced slope. Considerations of site preparation, reinforcement and fill placement, compaction control, face construction, and field inspection are given by Berg (1993) and Holtz et al. (1997).

10. REINFORCED RETAINING WALLS AND ABUTMENTS

10.1. Concept

Retaining walls are required where a soil slope is uneconomical or not technically feasible. When compared with conventional retaining structures, walls with reinforced backfills offer significant advantages. They are very cost effective, especially for higher walls. Furthermore, these systems are more flexible than conventional earth retaining walls such as reinforced concrete cantilever or gravity walls. Therefore, they are very suitable for sites with poor foundations and for seismically active areas.

Modern reinforced soil technology was developed in France by H. Vidal in the mid 1960s. His system is called Reinforced Earth and is shown in Fig. 4. Steel strips are used to reduce the earth pressure against the wall face. The design and construction of Vidal-type reinforced earth walls are now well established, and many thousands have been

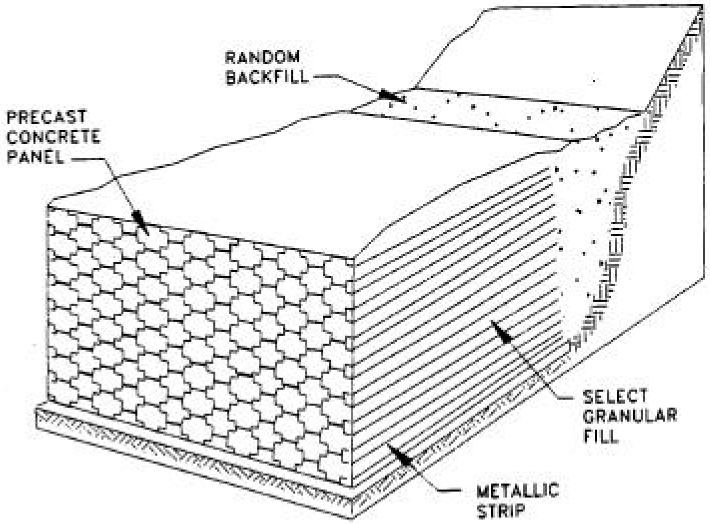

Fig. 4. Component parts of a Reinforced Earth wall.

successfully built throughout the world in the last 25 years. Other similar proprietary reinforcing systems have also been developed using steel bar mats, grids, and gabions. The use of geotextiles as reinforcing elements started in the early 1970's because of concern over possible corrosion of metallic reinforcement. Systems using sheets of geosynthetics rather than steel strips are shown in Fig 5.

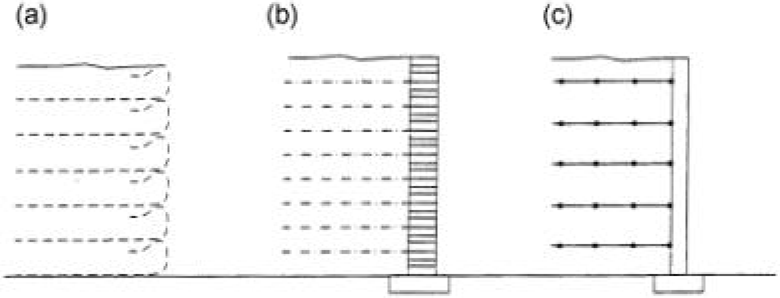

Fig. 5. Reinforced retaining wall systems using geosynthetics: (a) with wrap-around geosynthetic facing, (b) with segmental or modular concrete block, and (c) with full-height (propped) precast panels.

The maximum heights of geosynthetic reinforced walls constructed to date are less than 20 m, whereas steel reinforced walls over 40 m high have been built. A significant benefit of using geosynthetics is the wide variety of wall facings available, resulting in greater aesthetic and economic options. Metallic reinforcement is typically used with articulated precast concrete panels or gabion-type facing systems.

10.2. Design Considerations

Reinforced wall design is very similar to conventional retaining wall design, but with the added consideration of internal stability of the reinforced section. External stability is calculated in the conventional way--the bearing capacity must be adequate, the reinforced section may not slide or overturn, and overall slope stability must be adequate. Surcharges (live and dead loads; distributed and point loads) are considered in the conventional manner. Settlement of the reinforced section also should be checked if the foundation is compressible.

A number of different approaches to internal design of geotextile reinforced retaining walls have been proposed (Christopher et al., 1990; Allen and Holtz; 1991; Holtz, 1995), but the oldest and most common--and most conservative--method is the tieback wedge analysis. It utilizes classical earth pressure theory combined with tensile resisting “tiebacks” that extend back of the assumed failure plane (Fig. 6). The K_A (or K_o) is assumed, depending on the stiffness of the facing and the amount of yielding likely to occur during construction, and the earth pressure at each vertical section of the wall is calculated. This earth pressure must be resisted by the geosynthetic reinforcement at that section.

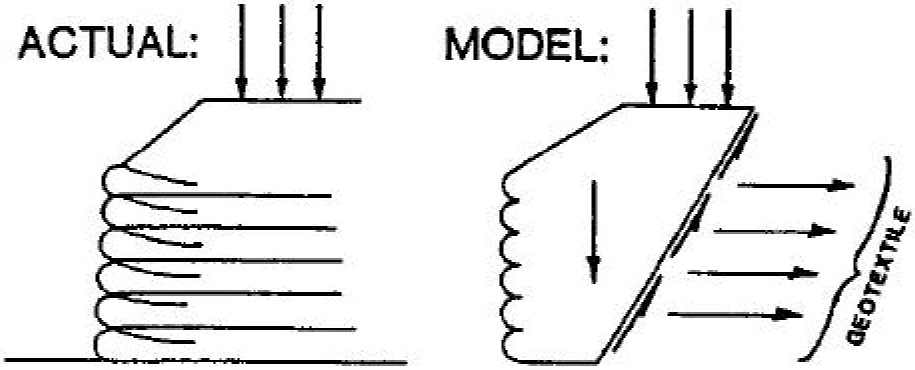

Fig 6. Actual geosynthetic-reinforced wall
compared to its analytical model.

To design against failure of the reinforcement, there are two possible limiting or failure conditions: rupture of the geosynthetic and pullout of the geosynthetic. The corresponding reinforcement properties are the tensile strength of the geosynthetic and its pullout resistance. In the latter case, the geosynthetic reinforcement must extend some distance behind the assumed failure wedge so that it will not pull out of the backfill. Typically, sliding of the entire reinforced mass controls the length of the reinforcing elements. For a detailed description of the tieback wedge method, see Christopher and Holtz (1985), Bonaparte et al. (1987), Allen and Holtz (1991), and Holtz et al. (1997). Recent research (e.g., Lee et al., 1999; Lee, 2000; Bathurst et al.,2000) has indicated that the tieback wedge approach is overly conservative and uneconomical, and modifications and deformation-based designs are rapidly being developed.

Other important design considerations include drainage and potential seismic loading.

10.3. Material Properties

Geosynthetic properties required for reinforced walls are similar to those listed in Table 1, Section 8.3 and discussed in Section 9.3 for reinforced slopes. Properties are required for design (stability), constructability, and durability. Allowable tensile strength and soil-geosynthetic friction are required for stability design, and similar to reinforced slopes, a partial factor or reduction factor approach is common. The ultimate wide width strength is reduced to account for uncertainties in creep strength, chemical and biological degradation effects, installation damage, and joints and connections. Berg (1993), Holtz et al.(1997), and Koerner and Hsuan (2001) give details about the determination of the allowable geosynthetic tensile strength. They also describe how soil-geosynthetic friction is measured or estimated.

The discussion on durability and longevity of geosynthetic reinforcement given in Section 9.3 is pertinent here.

Backfill for geosynthetic reinforced walls should be free draining if at all possible. If not, then adequate drainage of infiltrating surface or groundwater must be provided. This is important for stability considerations because drainage outward through the wall face may not be adequate. Soil properties required include gradation, percent fines, chemical composition, compaction, unit weight, and shear strength. To insure stability, appropriate consideration of the foundation and overall slope stability at the site is also important (Holtz et al., 2001b).

10.4. Wall Facing Considerations

A significant advantage of geosynthetic reinforced walls over conventional retaining structures is the variety of facings that can be used and the resulting aesthetic options that can be provided. Aesthetic requirements often determine the type of facing systems. Anticipated deflection of the wall face, both laterally and downward, may place further limitations on the type of facing system selected. Tight construction specifications and quality inspection are necessary to insure that the wall face is constructed properly; otherwise an unattractive wall face, or a wall face failure, could result.

Facing systems can be installed (1) as the wall is constructed or (2) after the wall is built. Facings installed as the wall is constructed include segmental and full height precast concrete panels, interlocking precast concrete blocks, welded wire panels, gabion baskets, treated timber facings, and geosynthetic face wraps. In these cases, the geosynthetic reinforcement is attached directly to the facing element. Systems installed after construction include shotcrete, cast-in-place concrete facia, and precast concrete or timber panels; the panels are attached to brackets placed between the layers of the geosynthetic wrapped wall face at the end of wall construction or after wall movements are complete. Facings constructed as the wall is constructed must either allow the geosynthetic to deform freely during construction without any buildup of stress on the face, or the facing connection must be designed to take the stress. Although most wall design methods assume that the stress at the face is equal to the maximum horizontal stress in the reinforced backfill, measurements show that considerable stress reduction occurs near the face, depending on the flexibility of the face. See Allen and Holtz (1991) and Holtz et al. (1997) for a detailed discussion of wall facing systems.

10.5. Constuction

Construction procedures for geosynthetic reinforced walls and abutments are given by Christopher and Holtz (1985) and Holtz et al. (1997). Procedures are relatively simple and straightforward, but failures are surprisingly common, especially with proprietary precast segmental concrete block-faced wall systems. It appears that most of these failures are due to (1) inadequate design, particularly of the foundation and back slope of the wall, and/or (2) problems in construction. The latter include poor inspection and quality control, poor compaction, use of inappropriate backfill materials, lack of attention to facing connections, and lack of clear lines of responsibility between designers, material suppliers, and contractors.

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