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Design Guidance for Reinforced Soil Structures with Marginal Soil Backfills

Barry R. Christopher, Ph.D., P.E.
Christopher Consultants, Roswell, Georgia, USA

Jorge G. Zornberg, Ph.D., P.E.
GeoSyntec Consultants, Huntington Beach, California, U.S.A.

James K. Mitchell, Ph.D., P.E.
Virginia Polytechnic Institute and State University, Blacksburg, Virginia, U.S.A.

ABSTRACT: Use of marginal, poorly draining backfill to construct reinforced soil structures offers significant advantages for numerous applications. This paper reviews the issues associated with using such soils with an emphasis on the use of permeable inclusions as a design alternative to provide internal drainage of the reinforced zone. Case histories demonstrating the successful use of permeable inclusions for addressing both internal and external seepage problems are presented. Adverse conditions of excessive moisture and pore water pressures within the poorly draining backfill are identified. Finally, preliminary guidance for reinforced soil structures using poorly draining backfills is provided to account for these adverse conditions in their design.

KEYWORDS: Reinforcement, Design, Seepage Control, Shear Strength, Drainage.

1 INTRODUCTION

Granular soils have been the preferred backfill material for reinforced soil construction due to their high strength and ability to prevent development of pore water pressures. Stringent specifications regarding selection of granular backfill are provided, for example, by the United States FHWA guidelines (Elias and Christopher, 1996). However, if granular fills were not readily available, or if substantial cost benefits resulted from relaxing fill specifications, poorly draining soils (e.g. silty or clayey soils) have been used in practice. In these cases, proper understanding of the conditions leading to wetting of the fill and to the development of pore water pressures is imperative for an adequate design.

Although marginal soils have been successfully reinforced using impermeable reinforcements (e.g. geogrids, woven geotextiles, metallic reinforcements), failures have also been reported. These failures generally occurred if the generation of pore pressures or seepage related conditions were not correctly addressed during design (Mitchell and Zornberg, 1995).

A promising approach for design of reinforced marginal soils is to promote lateral drainage in combination with soil reinforcement. This may be achieved by using geocomposites with in-plane drainage capabilities or thin layers of granular soil in combination with the geosynthetic reinforcements. This design approach may even lead to the elimination of external drainage requirements. The potential use of permeable inclusions to reinforce poorly draining soils is well documented (e.g. Tatsuoka et al., 1990; Zornberg and Mitchell, 1994; Mitchell and Zornberg, 1995). The focus of this paper is on the implementation of this technology by providing design guidance based on experience gained in recent case histories. Emphasis is placed on the identification of the adverse conditions that may result in wetting and pore water pressure development within the reinforced marginal fill.

This paper initially identifies the problems related to the use of marginal soils and the potential use of permeable inclusions as a design alternative. Next, experiences from the technical literature and by the authors on recent case histories are presented. Finally, preliminary guidance is provided, considering the identified adverse conditions, regarding the design of reinforced soil structure using poorly draining backfills.

2 BACKGROUND

2.1 Reinforcing Poorly Draining Backfills: Identification of Adverse Conditions

Significant problems are associated with the use of marginal soils in reinforced soil construction. The use of comparatively wet soils leads, for example, to construction problems associated with compaction difficulties during placement. However, the most serious concerns are related to stability problems associated with the potential development of pore water pressures or loss of strength due to wetting within the reinforced fill mass. The following three adverse conditions of pore water pressure generation and/or loss of strength due to wetting are of concern when reinforcing poorly draining backfills (Fig. 1):

Condition (a): Generation of pore water pressures within the reinforced fill. When fine grained, poorly draining soils are used in reinforced soil construction (particularly if placed wet of optimum moisture), excess pore water pressure can develop during compaction, subsequent loading, and surcharging. The designer must then account for these pore water pressures for the evaluations of stability and consolidation-induced settlements.

Condition (b): Wetting front advancing into the reinforced fill. This is the case for fills placed comparatively dry (i.e. no pore water pressure generation is expected during construction). However, loss of soil shear strength may occur due to wetting of the backfill soils as a consequence of post-construction infiltration. This loss of strength due to wetting could be expected, even if no positive pore water pressures are generated and no seepage flow configuration is established within the fill.

Condition (c): Seepage configuration established within the reinforced fill. Seepage flow may occur within the reinforced soil mass, for example, in the case of sliver fills constructed on existing embankment side slopes and cut slopes in which infiltration occurs from the adjacent ground. Significant seepage forces may occur either during rainy or spring thaw seasons. Water level fluctuations and rapid draw down conditions can also induce seepage forces in structures subjected to flooding or constructed adjacent to or within bodies of water. Seepage forces may also occur during ground wetting, inducing an additional destabilizing effect to the loss in shear strength described by Condition (b).

2.2 Reinforcing Poorly Draining Backfills: Permeable Inclusions as Potential Design Alternative

The potential benefits of using marginal soils to construct steepened slopes are significant and include:

- reduced cost of structures that would otherwise be constructed with expensive select backfill;
- improved performance of compacted clay structures that would otherwise be constructed without reinforcements; and
- use of materials, such as nearly saturated cohesive soils and mine wastes, that would otherwise require disposal.

However, the significant benefits of using poorly draining soils as backfill material can be realized only if a proper design accounts for the three adverse conditions listed in Section 2.1. The use of permeable reinforcements is a potential design alternative to properly handle these conditions, as follows:

Condition (a): Pore water pressures generated during construction within the reinforced poorly draining fill could be dissipated if the geosynthetic inclusions are used not only as reinforcements, but also as lateral drains. New applications in the use of geosynthetics for stabilization in land reclamation projects could be developed. For example, acceleration of drainage of hydraulically dredged materials could be achieved.

Condition (b): A problem frequently reported for embankments of (unreinforced) compacted cohesive soils is the development of surface tension cracks and the subsequent loss of soil strength due to soaking. The wetting front and development of surface tension cracks have been observed by the authors and other investigators (Tatsuoka et al., 1990) to extend only down to the region above the first geosynthetic layer. If the reinforcement is permeable, water that might normally accumulate in the crack can drain when the crack reaches the first layer of reinforcement.

Condition (c): Permeable reinforcements can prevent the development of flow configurations with destabilizing seepage forces within the embankment fill. Internal drainage is of particular concern in road widening projects, because of the potential water seepage from cut slopes into the reinforced fill. Although the adverse effect of seepage forces in engineered slopes could be prevented by designing special drainage systems, a more economical design alternative is to combine drainage and reinforcement capabilities by using permeable reinforcement elements.

In addition to addressing stability problems, the use of permeable inclusions may also be of benefit during construction. Wet soils typically must be dried to provide desired compaction levels and associated design strengths. However, it has been verified that permeable inclusions (e.g. nonwoven geotextiles) help in the compaction of the

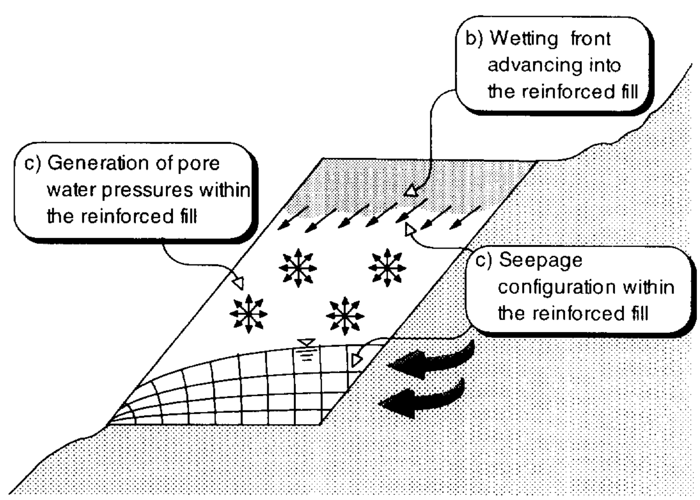

Fig. 1. Different conditions of concern in reinforced soil slopes using poorly draining backfills.

fill both by allowing better distribution of the compaction effort and by draining excess pore water pressure induced during compaction (Indraratna et al., 1991; Zornberg et al., 1995). On several projects, water has even been observed seeping out of the geotextile during compaction of such soils placed wet of optimum. The most significant improvement in compaction has been reported for low plasticity clayey and silty soils. Although some compaction improvement has been observed in plastic soils, the influence would not be nearly as significant. In either case, drying may still be required to facilitate placement and compaction, especially in very wet soils. Test pads are recommended to determine the actual placement requirements and compaction improvements. The increased rate of settlement would also expedite the construction of structures with a low tolerance for settlement (e.g. roads, bridges and buildings) that may be supported by the reinforced structure.

3. EXPERIENCE IN THE USE OF REINFORCED POORLY DRAINING FILLS

Although there are no generally accepted design guidelines for reinforced soil structures using marginal soils, good performance has been observed in cases where the generation of pore water pressures within the fill was mitigated. The observed performance of a 5.6 m high experimental structure built using silt backfill in Rouen, France is a good example (Perrier et al., 1986). Pore water pressures were monitored within the silt backfill. The structure consisted of sections reinforced with woven geotextiles and a section reinforced with a composite nonwoven/geogrid. Fig. 2 shows positive and negative pore water pressures as a function of time recorded at different locations within the fill. The pressure sensor behind the reinforcement region recorded placement excess pore water pressures of as much as 60 kPa at the end of construction. Along the woven geotextile, 3.5 m from the wall face, positive pore water pressures on the order of 20 kPa were registered at the end of construction and dissipated in 350 days. Along the composite geotextile, on the other hand, negative pore water pressures were registered over the entire length of the reinforcement, even at the end of construction. The negative pore water pressure recorded for the geocomposite most likely developed due to the ability of the geosynthetic to maintain partial saturation in the soil or to the unsaturated condition of the geosynthetic itself. Pore water pressures along the composite geotextile were systematically lower than those recorded along the woven textile.

Permeable reinforcements were also used to control pore water pressure during construction and to accelerate post-construction consolidation as part of the reconstruction of an embankment in Pennsylvania (Wayne et al., 1996). A sink hole developed in a section of state route SR54 due to the collapse of an abandoned railroad tunnel. The traditional repair would have involved the removal and replacement of the 15 m high embankment. However, the native soil (a sandy clay of high moisture content) was deemed unsuitable backfill due to potential stability and settlement problems. Consequently, due to the high cost of granular fill as replacement material(estimated as \$19.60/m^3), the Pennsylvania DOT decided to use geosynthetics to provide both drainage and reinforcement to the native soil used as fill. The estimated cost savings are \$200,000 (based on an as built cost of \$4/m^3 for the native

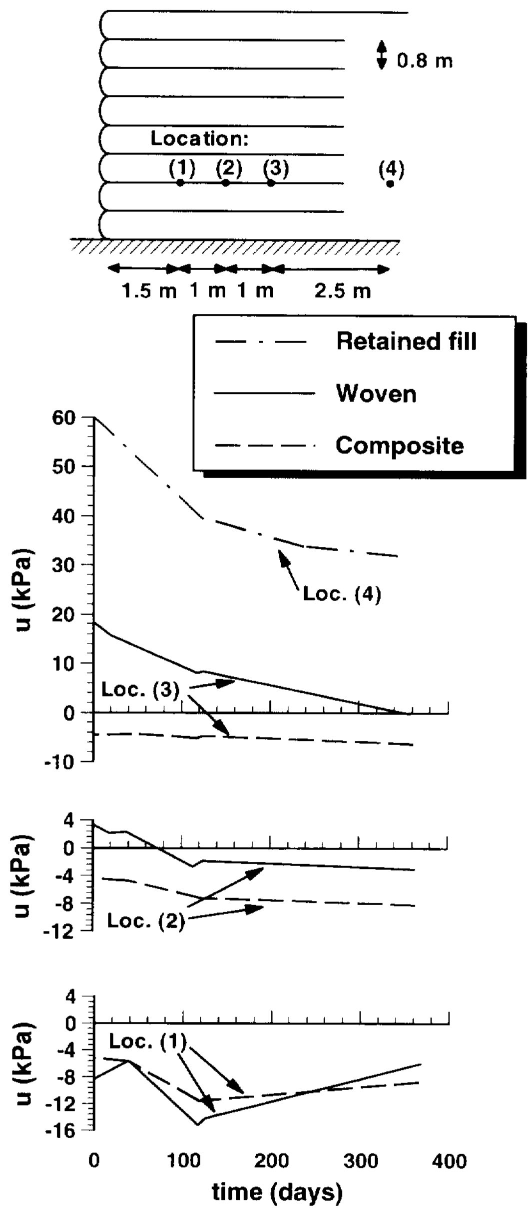

Fig. 2. Pore water pressures (u) in the Rouen reinforced wall, along a woven and a nonwoven/geogrid composite, within a silty backfill (redrawn after Perrier et al., 1986).

soil plus the geotextile). Based on the results of field tests used to evaluate pore pressure response, a nonwoven geotextile was selected to allow pore pressure dissipation in the native soil. The geotextile, with an ultimate strength of 16 kN/m, also provided reinforcement to the 1.5H:1V side slopes. Placement of geotextiles at each compacted lift (0.3 m spacing, i.e. 0.15 m drainage path), led to full dissipation of pore water pressure within approximately 4 days. Only approximately 25% of the pore water pressures were dissipated during the same time period in zones that did not contain geosynthetics. Piezometers installed at the base and middle of the slope confirmed the test pad results. Fig. 3 shows the development and subsequent dissipation of pore pressure during and following construction of the embankment. Geotextile deformations in the side slope were monitored and found to be less than the precision of the gages (± 1% strain).

There is also good evidence that permeable geosynthetic reinforcements can reduce the influence of external seepage behind the reinforced soil mass (e.g. in cut slope applications). Recent centrifuge model studies evaluated the performance of unreinforced and reinforced steep slopes constructed with clay (Mahmud, 1997). Seepage was induced into the reinforced clay by maintaining a constant water level at the back of the structure. Measurement of pore pressure across the base of the structure, indicated a lower phreatic surface if the slope was constructed using permeable geosynthetic reinforcements than if the slope was unreinforced (Fig. 4).

The use of permeable reinforcements to reduce external seepage problems was also demonstrated in a recent project which included one of the highest geotextile-reinforced slopes in the U. S. (Zornberg et al., 1995). As part of a highway widening project, the Federal Highway Administration constructed a permanent, 15.3 m high geotextile-reinforced slope. Several characteristics were unique to the design: the structure was higher than usual geotextile-reinforced slopes, it involved the use of both a high modulus composite and a nonwoven geotextile, and it was constructed using indigenous soils (decomposed granite) as backfill material. Internal drainage was a design concern because of the potential seepage from the fractured rock mass into the reinforced fill, and because of the potential crushing of decomposed granite particles that was anticipated to reduce the hydraulic conductivity of the fill. Widening of the original road was achieved by converting the existing 2H:1V unreinforced slope into a 1H:1V reinforced slope. The final design adopted a high strength composite geotextile in the lower half of the slope and a nonwoven geotextile in the upper half. Piezometer measurements indicated that a seepage flow configuration did not develop within the reinforced soil mass even during the spring thaw, when seepage water infiltrated from the backslope fractured rock into the reinforced fill.

Additional evidences that good structure performance is dependent on maintaining a low water pressure in poorly draining backfills was provided by Tatsuoka et al. (1990) and Mitchell and Zornberg (1995). However, practice has led theory, and a consistent design methodology for design of reinforced soil structures using poorly draining backfills has not been developed yet.

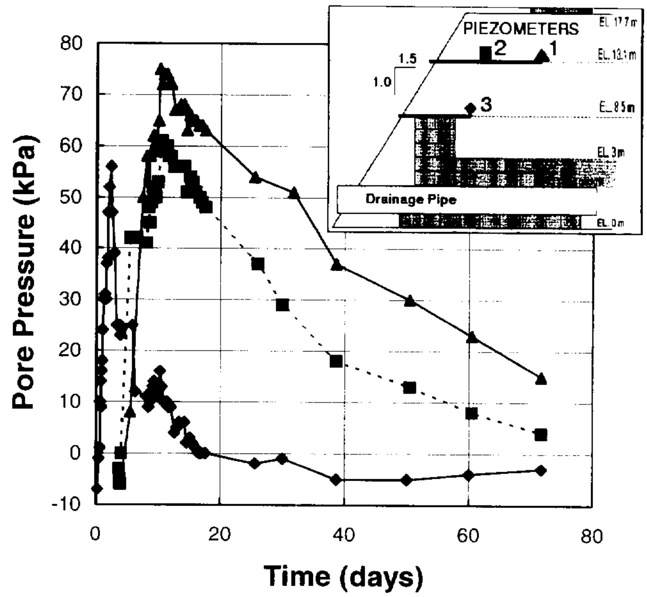

Fig. 3. Pore water pressure measurements in the SR54 reinforced slope (redrawn after Wayne et al., 1996).

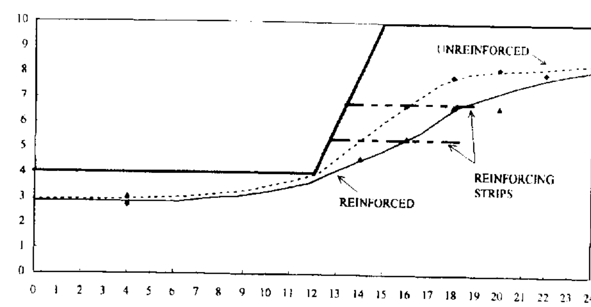

Fig. 4. Centrifuge model results showing the elevation of the phreatic surfaces for unreinforced and reinforced slopes (Mahmud, 1997).

4. DESIGN GUIDANCE

4.1 General Considerations

Good performance in reinforcing marginal soils depends on accounting for excess pore water pressure development within the fill material. Design criteria involved in the use of reinforcement-drainage geocomposites differ from those developed for conventional soil reinforcement applications. A total stress analysis, considering soil parameters representative of placement conditions, usually has been adopted in the analysis of impermeable conventional reinforcements. The design generally leads to the use of reinforcements with a comparatively high tensile strength to account for a low soil shear strength and the presence of seepage forces. Reinforcement embedment length is comparatively large to account for reduced pullout resistance. External drainage of the reinforced soil structure has often been considered as part of the design to intercept ground water at the back of the structure.

The general design philosophy for permeable inclusions that is proposed in this paper is that transmissivity of the geosynthetic inclusion should be selected so that the geosynthetic inclusions can carry the full in-plane flow without developing positive pore water pressures along the soil-reinforcement interface. While it is also possible to design for positive pore water pressures at the interface, such a design requires evaluations that are beyond the scope of this paper. Consequently, the design procedure described below is only for reinforced soil structures in which the reinforcement transmissivity is conservatively selected so that flow is not impeded within the geosynthetic. The proposed design methodology assumes no build up of excess pore pressure within the permeable reinforcements.

The analysis should account for the three adverse conditions listed in Section 2.1 in order to determine the tensile strength and pullout requirements. The general design philosophy proposed herein is to consider a two-phase evaluation:

Analysis (i) in each adverse condition is performed ignoring the drainage contribution provided by the reinforcements. This is a total stress analysis which considers that stability is mostly provided by the reinforcements with minimum contribution of the soil shear strength. Due to the conservative nature of this assumption, a relatively low design factor of safety is suggested.

Analysis (ii) in each adverse condition is performed accounting fully for the drainage contribution provided by the reinforcements (i.e. zero pore water pressure is considered within the reinforced fill for analysis purposes). Considering that no pore water pressures are assumed to develop, this is an effective stress analysis. Design factors of safety used in conventional engineering practice are considered in this case.

4.2 Designing for Condition (a): Pore water Pressures Generated within the Reinforced Fill

There is good evidence that geosynthetics with adequate transmissivity and vertical spacing on the order of every compaction lift or every other compaction lift (e.g. 200 to 300 mm) can dissipate excess pore pressure along the interface of the permeable inclusions during construction (Bourdillon et al., 1977). However, excess pore water pressures may develop within the soil mass between geosynthetic layers during construction, especially if highly plastic soils are used as backfill material. Considering the difficulty in accurately evaluating the distribution of pore water pressures generated during construction a two-phase analysis is proposed. These analyses, summarized in Table 1, are as follows:

i) Total stress analysis ignoring reinforcement lateral drainage. This analysis neglects the dissipation of pore water pressures through the permeable inclusions to provide a conservative estimate of the stability of the structure at the end of construction. Considering the short-term condition and the conservative assumptions in this analysis, a factor of safety of 1.1 is recommended. This analysis determines minimum reinforcement requirements that will preclude collapse during construction of the structure. That is, it provides reinforcement requirements for a short-term situation in which stability is provided mostly by the tensile forces in the reinforcements with only a minor contribution by the undrained shear strength of the backfill. The undrained soil shear strength of the backfill for this analysis should be based on unconsolidated undrained (UU) triaxial tests. The specimens should be prepared at representative field densities and moisture placement conditions, and tested at these placement conditions under project-specific confining pressures. Although the authors consider testing under unsaturated conditions is an adequate approach, testing under fully saturated conditions represents an additional degree of conservatism that the designer may consider on a project-specific basis.

ii) Effective stress analysis accounting for full lateral drainage by the reinforcement. Full drainage of the reinforced fill is assumed for the long-term conditions. This analysis provides a realistic evaluation of the long-term stability of the structure, because dissipation of pore water pressures generated during construction should have occurred through the permeable inclusions. This analysis determines the minimum reinforcement requirements that will provide adequate stability under long-term conditions following dissipation of pore water pressures generated during construction of the structure. It is emphasized that the transmissivity of the reinforcements should be selected so that generation of pore water pressures is prevented at the soil-reinforcement interface. Typically, the soil shear strength should be based on isotropically consolidated undrained (CIU) triaxial tests performed on saturated samples with pore pressure measurements or on consolidated drained (CD) triaxial tests. The long term design factor of safety typically required for reinforcement of granular fills (e.g. 1.3 to 1.5) should be used in this analysis.

Table 1. Summary of Analyses for Reinforced Soil Structures with Poorly Draining Backfills

Condition	*Characteristics*	*Analysis i: Ignoring lateral drainage*	*Analysis ii: Accounting for full drainage*
a) Generation of pore water pressures within reinforced fill	Type of analysis:	Total Stress	Effective Stress
	Case:	Generation of pore pressures due to short-term loads	Long-term drained condition due to lateral drainage
	Design Criteria:	FS = 1.1	FS = 1.3 to 1.5 (*)
	Reinforcement Transmissivity:	Ignored in analysis	Conveys fully the flow from consolidation process
	Soil shear strength:	ϕ and c from UU tests. Specimen condition: as placed	ϕ' and c' from CIU or CD tests. Specimen condition: saturated
b) Wetting front advancing into reinforced fill	Type of analysis:	Total Stress	Total Stress
	Case:	Loss of shear strength due to soaking	Unsaturated condition maintained due to permeable reinforcements
	Design Criteria:	FS = 1.1	FS = 1.3 to 1.5 (*)
	Reinforcement Transmissivity:	Ignored in analysis	Prevents advancement of wetting as defined by testing
	Soil shear strength:	ϕ and c from CIU tests. Specimen condition: saturated	ϕ and c from CIU or CD tests. Specimen condition: highest anticipated moisture
c) Seepage flow configuration established within reinforced fill	Type of analysis:	Total Stress	Effective Stress
	Case:	Development of seepage forces within fill	Saturation of fill, without development of seepage forces due to permeable reinforcements
	Design Criteria:	FS = 1.1	FS = 1.3 to 1.5 (*)
	Reinforcement Transmissivity:	Ignored in analysis	Conveys fully the seepage flowing into the backfill
	Soil shear strength:	ϕ and c from CIU tests. Specimen condition: saturated	ϕ' and c' from CIU or CD tests. Specimen condition: saturated

(*) Design criteria for Analysis (ii) should be selected based on design guidelines for reinforced soil structures with granular backfill.

The reinforcement tensile strength eventually selected is the higher value obtained from analyses (i) and (ii). Moreover, the minimum reinforcement length selected for design should be the larger value defined from the two analyses. Note that the analyses described above address internal stability. However, the required length of the reinforcement must also consider external stability of the structure. External stability should consider the undrained soil shear strength for the fill retained behind the reinforced zone if it is to be constructed with similar marginal fill. For cut slopes appropriate pore water pressure assumptions should be made for field conditions.

It should be noted that an effective stress analysis could have been proposed to evaluate the short-term stability of the structure, instead of the total stress Analysis (i). An effective stress analysis would more accurately account for the in-plane drainage capacity of the geosynthetic and the corresponding increase in soil strength. Also, an effective stress analysis would facilitate evaluation of the backfill placement rate that would lead to an acceptable stability factor of safety during construction. The difficulty in this approach is the accurate determination of the pore water pressures within the fill. They could be estimated from direct measurements in field trials (e.g. test pads) or sealed laboratory specimens (one lift thick with a geosynthetic on the bottom and top connected to drain lines) subjected to stress levels anticipated during construction. Alternatively, pore pressures could be theoretically estimated based on one-dimensional consolidation theory and the assumption of full saturation of the backfill material during construction. An evaluation of this approach is beyond the scope of this paper.

4.3 Designing for Condition (b): Wetting Front Advancing into the Reinforced Fill

As loss of strength may occur because of a wetting front advancing into the reinforced fill. Geosynthetic transmissivity requirements should be established to avoid advancement of wetting front for expected conditions. A two-phase analysis is also proposed in this case. These analyses, summarized in Table 1, are as follows:

i) Total stress analysis ignoring the effect of lateral drainage in preventing advancement of a wetting front. This analysis is performed using shear strength properties of the reinforced soil mass defined using saturated specimens. The results of this analysis provide a estimate of the stability of the structure under an advancing wetting front. This analysis is conservative because the backfill is assumed fully saturated, which should not occur in actual practice because the wetting front is intercepted by the permeable reinforcements. Consequently, a factor of safety of 1.1 is recommended in this case. Water pressure that may develop as water fills surface cracks (induced by desiccation, freeze/thaw, or slope movements) should be accounted using boundary water pressures in the analysis.
ii) Total stress analysis accounting for the effect of lateral drainage in preventing advancement of a wetting front. The total shear strength is defined from unsaturated specimens prepared at the highest moisture anticipated in the fill. Note that the total shear strength defined from unsaturated specimens should be higher than the effective shear strength of the fill. A total stress analysis is considered in this case, instead of an effective stress analysis, in order to account for the beneficial effect of the negative pore water pressures in the unsaturated reinforced fill. The shear strength of the reinforced fill above the top reinforced layer (which may become saturated) should be obtained from saturated specimens. This analysis provides a realistic evaluation of the stability of the structure because it accounts for the lateral drainage of the geosynthetic reinforcements.

4.4 Designing for Condition (c): Seepage Configuration Established within the Reinforced Fill

Post-construction pore water pressures could be generated by a seepage configuration developing within the backfill material. Such a flow configuration may develop seasonally during rainy periods or during spring though. A seepage configuration may also develop due to water level fluctuations in structures subjected to flooding or constructed adjacent to or within bodies of water. Finally, seepage forces could be induced by surface water infiltration. The seepage configuration can be determined for an unreinforced embankment using flow nets for seepage analysis. Transmissivity requirements in the geosynthetic inclusions are such that each reinforcement should convey fully the flow quantity it intercepts (as estimated from a flow net defined in an unreinforced slope). A two-phase analysis is also proposed in this case. These analyses, summarized in Table 1, are as follows:

i) Total stress analysis ignoring reinforcement lateral drainage. This analysis considers seepage forces defined from a flow configuration that would develop in an unreinforced slope. The results of this analysis provide a conservative estimate of the stability of the structure during a seasonal rapid configuration of seepage flow within the fill. The conservatism of this analysis is because (1) the backfill is assumed as fully saturated, which may not occur in actual practice, and (2) the seepage configuration does not account for the lateral drainage provided by the reinforcements. Therefore, a relatively low factor of safety of 1.1 is recommended in this case (note that seepage forces are considered in the analysis).
ii) Effective stress analysis accounting for full reinforcement lateral drainage. Full drainage of the reinforced fill is assumed for the typical condition of the structure. This analysis provides a realistic evaluation of the long-term stability of the structure because it accounts for the lateral drainage of the geosynthetic reinforcements. No seepage forces are considered to develop within the reinforced fill if the reinforcements provide adequate internal drainage.

As indicated, the transmissivity and number and location of layers should be selected so that the geosynthetics have in-plane drainage capacity to accommodate the full seepage flowing into the reinforced fill. Otherwise, external groundwater and surface water control systems (e.g. base and back drains and surface collectors) must be incorporated into the design. The soil shear strength in the two analyses (total and effective stresses) should be determined using saturated samples in order to account for the potential loss of shear strength under soaked conditions.

4.5 Reinforcement Requirements

Mechanical and hydraulic properties that must be characterized for alternative reinforcement-drainage geocomposite systems include: tensile strength, pullout resistance, drainage, and filtration. These four characteristics should be carefully evaluated and quantified in order to assess the overall performance of the structures under consideration. The evaluations include at least the following considerations:

- Tensile strength requirements of the geosynthetic, determined as indicated in Table 1, will be typically higher for reinforcement of marginal fills than conventional free draining material. Consideration should be given to soil creep in the determination of long-term design strength.

- Pullout resistance, which require special consideration due to the potential development of pore water pressures at the soil/reinforcement interface and to the creep potential of cohesive soils. For the total stress analyses in Table 1, total stress shear strength properties should be used. For the effective stress analyses, effective shear strength properties should be considered.
- Transmissivity requirements should account for the different conditions indicated in Table 1 (i.e. the total flow induced by consolidation or seepage must be accommodated without inducing positive pore water pressures within the reinforcements). There is good evidence that transmissivity values equivalent to those of needlepunched nonwoven geotextiles are adequate to freely drain cohesive type soil and dissipate excess pore pressure along the interface, provided spacing is on the order of every lift or every other lift of compacted soil (e.g. Bourdillon et al., 1977). They should also be high enough to prevent advancement of a wetting front. Test pads could be used to evaluate the suitability of selected geosynthetics. Increased transmissivity may be required based on flow net analysis of externally induced seepage (Condition c).
- Filtration requirements needed to minimize clogging of the geocomposite should also be evaluated. Design guidance is provided in Holtz et al. (1997) and Koerner (1994).

5 CONCLUSIONS

Marginal poorly draining backfill can be used to safely construct reinforced steepened slopes provided internal and external seepage forces have been accounted for in the analysis. Adverse conditions include: (a) the generation of pore water pressures within the reinforced fill (either during construction or subsequent loading); (b) a wetting front advancing into the reinforced fill, which may cause loss of soil shear strength in a fill initially placed in a comparatively dry condition; and (c) a seepage flow configuration established within the reinforced fill due to seepage from the retained soil or fluctuations in the water level for structures constructed adjacent to or within bodies of water.

Reinforcements with in-plane drainage capabilities offer a design alternative for mitigating these adverse conditions. A two-phase analysis is proposed when using permeable reinforcements to account for both short and long-term conditions. Although the design approach is supported by theoretical soil mechanics, it relies heavily on field experience. Therefore, an element of conservatism is inherently included in the proposed methods. Further refinement of this guidance is being developed by the authors in order to provide quantitative transmissivity requirements for the case of pore water pressures developed during construction. Recommendations are provided herein regarding the selection of soil shear strength properties and design criteria for the analyses.

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