The Applicability of Limit State Design to Polymer Reinforced Soil Structures

A. McGown, K. Z. Andrawes & S. M. Pradhan
University of Strathclyde, Glasgow, UK

ABSTRACT: The principles of Limit State design are briefly set out and the Limit State approach to the design of polymer reinforced walls, slopes and embankments is outlined. It shown to be highly applicable to reinforced soil structures, indeed it provides the possibilty of having a single integrated approach based on identifiable kinematic models. Clear recommendations are made for the choices of soil and material properties and the partial factors to be used. Justification for the adoption of the Limit State design approach is given in terms of the technical and cost benefits to be derived.

1 INTRODUCTION

Currently the design methods adopted for polymer reinforced soil structures are based on Limit Equilibrium approaches. Two groups of analysis are employed; one group is based on the Reinforced Earth wall analysis, first proposed by Schlosser and Vidal (1969), and the other group is based on modified slope stability analysis. These approaches assume that failure conditions occur simultaneously in all the soils and reinforcing materials. No analysis of working conditions nor the formulation of valid kinematic models for soil-polymer reinforcement interaction are required. Loads, polymer reinforcement properties and some soil properties are factored before incorporation in the analyses and overall factors of safety are adopted to obviate failure by a number of assumed mechanisms. Thus "actual" overall factors of safety for polymer reinforced soil structures are generally much higher than the "calculated" overall factors of safety and working stresses and strains in the reinforcements are generally very small, Yogarajah (1993). This suggests that polymer reinforced soil structures very often contain much more reinforcement than is strictly required and they are therefore less economic than they could be.

The introduction of the Limit State design approach to Geotechnical Engineering (e.g. Draft Eurocode 7, 1987) provides an ideal opportunity to overcome the inadequacies of the Limit Equilibrium approach. Firstly, Limit State design requires valid kinematic models of behaviour at ultimate and serviceability limits to be developed; secondly, it requires appropriate choices of soil and reinforcement properties, i.e. properties related to the strain conditions developed in each kinematic model, and thirdly, it employs partial factors on properties and/or forces so that there are no "hidden" factors of safety.

In this paper the principles of Limit State design are briefly set out. The Limit State approach to the design of polymer reinforced structures is described and shown to be highly applicable, indeed it is suggested that a single integrated approach based on identifiable kinematic models can be generated for walls, slopes and embankments.

2 PRINCIPLES OF LIMIT STATE DESIGN

A Limit State occurs when a structure, or part of a structure, fails to satisfy the fundamental requirements of either overall stability and deformability or internal stiffness and deformability, during construction or during its design lifetime.

Two Limit States may be defined:

a) Ultimate Limit State - at which a collapse mechanism forms in the ground or in the structure, or when movements of the structure lead to severe structural damage in the structure or in nearby structures or services.

b) Serviceability Limit State - at which movements of the structure affect the appearance or the efficient use of the structure, nearby structures or services.

Limit State design requires that the ground and the structure perform satisfactorily for both Ultimate and Serviceability Limit States. A number of possible conditions must be considered and these are termed Limit Modes. For each Ultimate and Serviceability Limit Mode, a valid kinematic model is identified and the loads, soil and other material properties adopted for use in the analysis of this mode are chosen to reflect the strain levels developed. These loads, soil and other material properties have partial factors of safety applied to them but thereafter no other factors of safety are applied.

3 LOADS

In addition to the self weight of the soil and other materials in the structure, all external loads must be taken into account. These may include sustained and transient uniformly distributed, line and point loads on the upper and lateral boundaries of the reinforced structure together with any shear forces along these boundaries. Other loads and loading conditions which may be appropriate in certain circumstances and should be included are siesmic loading, cyclic loading, flooding and three dimensional effects.

4 SOIL AND MATERIAL PROPERTIES

4.1 Sub-soil

The shear strength and compressibility of the sub-soil will be important design parameters just as for any geotechnical structure. No special consideration need be given to it on the basis that it supports a reinforced soil structure.

4.2 Reinforced soil

To date, compacted granular soils are normally employed in reinforced soil structures. The soil reinforcement mechanism is strain controlled, the strains being lateral tensile strains. Thus the important soil property is the relationship between the mobilised angle of friction and the lateral tensile strain in the compacted granular fill.

The relationship between these parameters may have two limiting forms depending on whether the stress strain behaviour of the soil is load or strain controlled. For both conditions the mobilised angle of friction of the soil (ϕ'_m) increases rapidly with strain from its at rest value ($\phi'_{at\ rest}$)to its peak value (ϕ'_p). For the load controlled condition the peak value remains constant to large strains, whereas for the strain controlled condition the angle of friction rapidly decreases to the angle of friction at constant volume (ϕ'_{cv}). Obviously, the strain controlled relationship is the more conservative and for that reason it should be adopted. Usually, the triaxial or shear box apparatuses are used to determine the peak angle of friction (ϕ'_p) and the angle of friction at constant volume (ϕ'_{cv}). The relationship between the mobilised angle of friction and tensile strain is then assumed, with the peak angle taken to develop at tensile strains of 3 to 6% and the angle of friction at constant volume at 8 to 10% tensile strain, Bolton (1986)

4.3 Reinforcements

Two basic types of reinforcements are employed in reinforced soil structures; relatively inextensible and relatively extensible reinforcements, McGown et.al. (1978). Relatively inextensible reinforcements may yield or even rupture under the operational stress-strain conditions. Relatively extensible reinforcements will not rupture under the operational stress-strain conditions. Most polymer reinforcements are relatively extensible at normal working temperatures but at low temperature conditions the load-strain behaviours of some materials may alter to the extent that they change from being relatively extensible to relatively inextensible reinforcements.

Polymer reinforcements are also time and temperature dependent materials, therfore short term tensile tests are not appropriate for the determination of their long term tensile load-strain behaviour on the basis that data from them are not simply related to long term behaviour. Sustained load (creep) testing at appropriate temperatures is required to determine their long term load-strain-time behaviour, McGown et al (1984), Murray and McGown (1987 a and b).

In order to develop tensile stress a high degree of interaction between the reinforcement and the soil is required. This may consist of surface friction only or a combination of surface friction and interlock depending on the structural form of the reinforcement material.

4.4 Connections

The connections must be capable of transmitting the stresses (loads) from the ends of the reinforcements to the facing, during the design lifetime of the structure under the strain (deformation) conditions operating at the rear of the facing. Their tensile load-deformation behaviour and flexural properties require to be determined. The choice of short term or sustained load (creep) testing depends on whether or not they are made from time and temperature dependent materials.

4.5 Facings

Unfaced slopes and embankments represent the condition of no restraint on the lateral boundary. Faced steep slopes and walls are restrained by a variety of lateral boundary conditions, the actual condition depending on the form of connections used and the nature of the facing employed. The factors relevant to the nature of the facing are its axial compressibility, lateral compressibility, flexural rigidity and frictional characteristics. The frictional resistance of the rear of the facing is usually high, and should be determined using shear box testing. Various combinations of the other three factors are possible as indicated in Fig. 1. The measurement of these properties can be made using conventional testing techniques but it is important to incorporate any jointing materials between components of the facing in any test specimens.

5 PARTIAL FACTORS

In Limit State analysis partial factors of safety are applied to the loads (γ_{fL}), materials strengths (γ_m) and the analysis model (γ_{f3}). γ_{fL} takes account of the possibility of an unfavourable deviation of the loads from their nominal values and of the reduced probility that various loadings acting together will attain their nominal values simultaneously. γ_{f3} takes account of inaccurate assessment of the effects of loading, unforseen stress distribution in the structure and variations in dimensional accuracy in construction. γ_m takes account of possible reductions in the strength of the soils and the materials in the structure. It comprises two components γ_{m1} and γ_{m2}. γ_{m1} takes account of possible reductions in the strength of the soils and materials in the structure as a whole, as compared with the values deduced from control tests specimens. γ_{m2} takes account of possible weaknesses of the structure arising from any cause other than the reduction in the strength of the soils and materials allowed for in γ_{m1}, for example compaction standards or manufacturing tolerances.

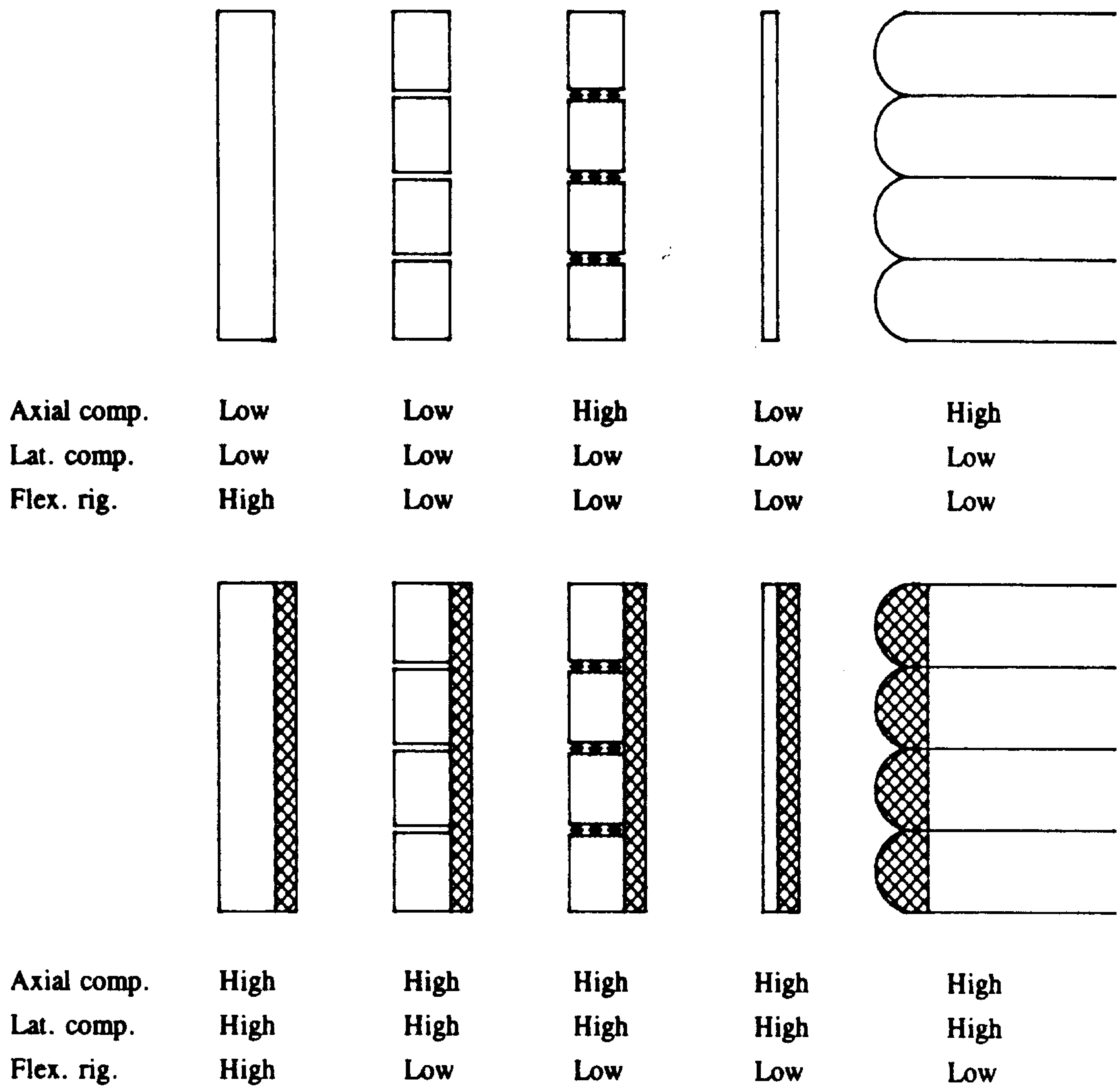


Fig. 1 Factors relevant to the nature of the facing

5.1 Loads

The Design Load Effects, S^*, are determined from the Nominal Loads , Q_k, according to the following:

$$S^* \;=\; \gamma_{f3}\ (effects\ of\ \gamma_{fL}.Q_k)$$

The value of γ_{f3} is usually taken to be 1.1 for the Ultimate Limit State and 1.0 for the Serviceability Limit State.

5.2 Soils

The Design Resistance, R^*, of the sub-soil or the reinforced fill is determined according to the following:

R^* = function [ϕ'_{des}] for drained conditions, or
R^* = function [Cu_{des}] for undrained conditions

where ϕ'_{des} is the design drained angle of friction of the sub-soil or the reinforced fill and Cu_{des} is the design undrained shear strength of the subsoil.
The value of ϕ'_{des} is determined from the appropriate value of mobilised angle of friction ϕ'_m:

$$\tan \phi'_{des} \quad [\frac{\tan \phi'_m}{\gamma_m}]$$

The value of Cu_{des} is determined from the appropriate value of mobilised undrained strength of the sub-soil Cu_m according to the following:

$$Cu_{des} \;=\; [\frac{Cu_m}{\gamma_m}]$$

5.3 Reinforcements

The design resistance of the reinforcing elements R^* is defined as:

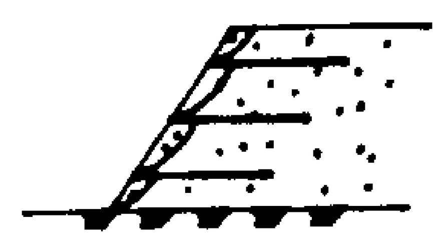
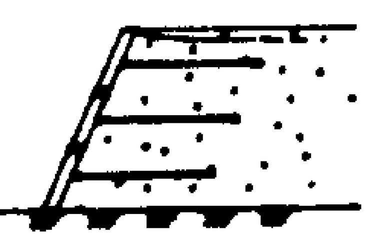
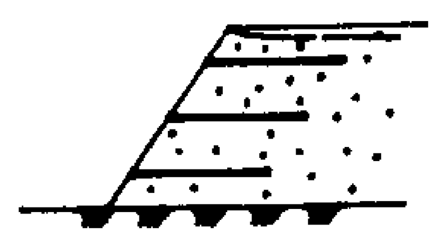
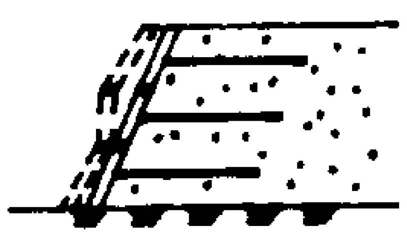
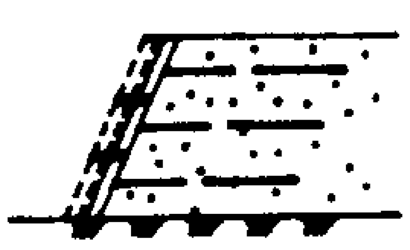
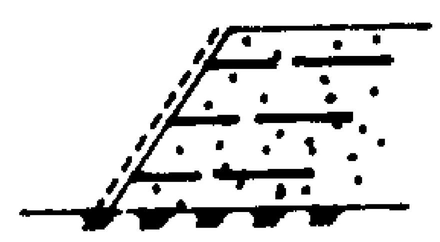
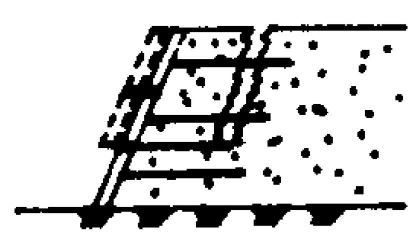
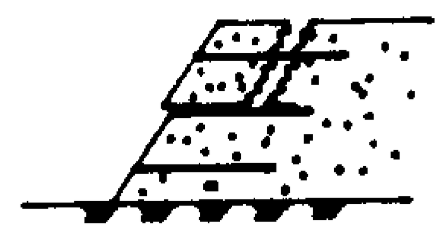
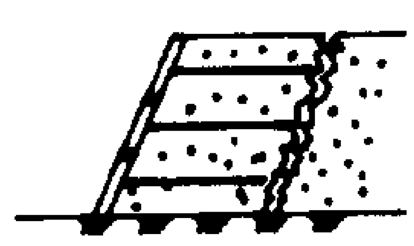
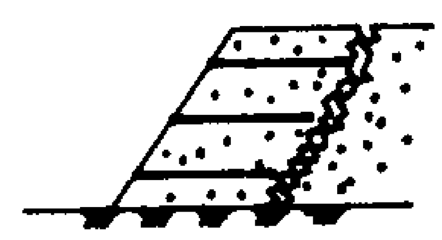
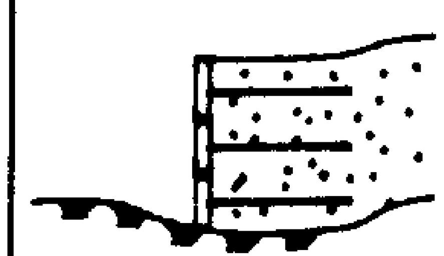
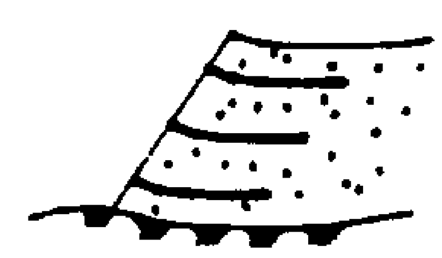
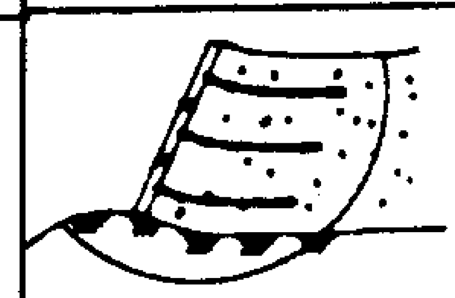
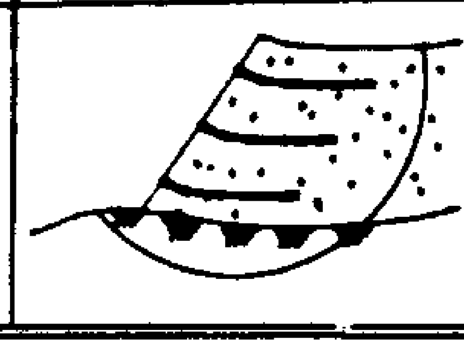
ULTIMATE LIMIT	SERVICEABILITY LIMIT	WITH FACING	NO FACING
1. LOCAL STABILITY AT FACE OF THE FILL		—	
2.	COMPRESSIBILITY OF THE FILL		
3. INTEGRITY OF FACING	DISPLACEMENT AND DEFORMATION OF FACING		—
4. RUPTURE OF REINFORCEMENT AND/OR CONNECTIONS	DEFORMATION OF REINFORCEMENT AND/OR CONNECTIONS		
5. REINFORCEMENT PULL-OUT	SOIL-REINFORCEMENT SLIPPAGE		
6. BASE SLIDING			
7. BEARING FAILURE OF SUB-SOIL	SETTLEMENT OF SUB-SOIL		
8. OVERTURNING			—
9. OVERALL STABILITY			

Fig 2 Suggested Limit Modes

$$R^* = \text{function} \ [\frac{f_k}{\gamma_m}]$$

where f_k is the nominal strength of the polymer reinforcement at the appropriate strain, time and temperature as determined by sustained load (creep) testing.

The design interaction resistance between the soil and the reinforcement is treated in the same manner.

5.4 Connections and facings

Special consideration needs to be given to the application of partial factors to connections and facings that are time and temperature dependent, otherwise γ_m is applied to their nominal properties to obtain their design properties.

5.5 Design criterion

For satisfactory design the following relationship must be satisfied for all Limit Modes:

$$R^* > S^*$$

6 LIMIT MODES TO BE CONSIDERED IN DESIGN

The use of Limit State analysis provides the basis for an integrated approach which deals consistently with walls, slopes and embankments. It is suggested that the Limit Modes which should be considered are as identified in Fig. 2. Which of these criteria are critical will depend on many factors hence, it is necessary to assess each of them on each occasion.

7 SPECIAL CONSIDERATIONS RELATING TO POLYMER REINFORCED SOIL STRUCTURES

When using Limit State analysis for the design of polymer reinforced soil structures it is necessary to distinguish between the tensile stiffness of the individual "Reinforcing Elements" and the tensile stiffness of the "Reinforcing System" as a whole. A reinforcing element is defined as a single layer or strip of reinforcing material and the reinforcing system is defined as the complete set of reinforcing elements in a reinforced soil structure.

The "Tensile Stiffness of a Reinforcing Element" is the tensile force developed by the element divided by its mobilised tensile strain. Its value is dependent on the constituent material and structural form of the reinforcing element. The "Tensile Stiffness of a Reinforcing System" is the summation of the tensile forces developed in the reinforcing elements divided by their average mobilised tensile strain. Its value is dependent on the constituent material and structural form of the reinforcing elements and on their concentration in the reinforced soil structure.

This is important as the stiffness of a reinforcing system influences the soil strains required in the reinforced soil structure to develop force equilibrium. The tensile strains in the reinforcing elements are taken to be equal to the tensile strains in the adjacent soil, i.e. it is assumed that there is no slippage between the soil and the reinforcing elements.

The forces required for equilibrium in a reinforced soil structure which includes relatively extensible reinforcing elements can be mobilised at either low or high strains depending on the constituent material and structural form of the reinforcing elements and their concentration. Thus relatively extensible reinforcing systems can range from high to low tensile stiffness, which greatly influences the choice of soil and reinforcing materials properties in the analysis.

There are two forces acting on the facings; one is generated by the fill material and the other is generated by the reinforcing elements through the connections. The actual values of these forces depend on four factors; the method of connecting the reinforcing elements to the facing, the effectiveness of the reinforcing system in increasing the shearing resistance of the soil, the ability of the boundary to deform and compaction stresses.

The influence of the connections on lateral boundary forces and the load distribution along the reinforcing elements depend on the form of the connections:

a) No connections: No load is transferred from the reinforcing elements to the facing and the forces at the end of the reinforcing elements are always zero.

b) Vertically sliding connections: These allow vertical movement of the soil relative to the rear of the facing but avoid local bending stresses at the ends of the reinforcing elements. Further, they minimise modification of the lateral boundary stresses and generate minimal loads at the end of the reinforcing elements.

c) Loose connections: These minimise modifications of the lateral boundary stresses and generate minimal loads at the ends of the reinforcing elements.

d) Rigid connections: These may significantly modify lateral boundary stresses and may generate significant loads at the ends of the reinforcing elements.

e) Connections tightened up during or after placement of the fill: These may greatly increase lateral boundary stresses possibly up to passive pressure conditions and can generate very large loads at the ends of the reinforcing elements.

The compaction stresses will modify lateral boundary stresses and the load distribution along the reinforcing elements. They may be overcome by allowing significant lateral boundary movement or imposing stresses greater than the locked-in stresses.

8 DEFORMATIONS AND STRAINS IN THE REINFORCED SOIL STRUCTURE

The deformations and strains in the reinforced soil system require to be known in order to form the basis on which Serviceability or Ultimate Limits may be set.

The deformations and strains that need to be considered are deformations of the fill material, the lateral boundary, the fill-sub soil boundary and strains in the reinforcing system. Assuming no slippage occurs at the soil-reinforcing elements interface, then the tensile strains in the reinforcing elements are equal to the tensile strains in the soil in the direction of the reinforcing elements. An assumption has to be made regarding the distribution of strains in order to determine the distribution of the mobilised loads in the reinforcing system. Frequently the assumption is made that strains are uniformly distributed throughout the reinforced soil structure. This assumption is highly questionable.

The actual strains occurring in the reinforced soil structure depend on the characteristics of the fill material, the stiffness of the reinforcing system, the fill/reinforcing elements interface properties and the lateral boundary restraint conditions.

Deformations of the lateral boundary can occur due to any one, or a combination, of the use of a reinforcing system with low stiffness, a facing with high axial compressibility, high lateral compressibility or low flexural rigidity. When using a facing with high axial or lateral compressibility, distinction should be made between the deformations of the inner and outer surfaces of the boundary.

9 CONCLUSIONS

An important requirement when using Limit State analysis is the identification of the appropriate material properties and the mechanisms of deformation and failure relevant to the state under consideration. This is not an easy task when dealing with polymer reinforced soil structures. Although the characteristics of the various components can be defined relatively easily, determining the behaviour of the reinforced structure is much more complex. For example, the stiffness or the reinforcing elements does not uniquely determine the stiffness of the reinforcing system in a reinforced soil structure. As has been suggested, a high concentration of relatively extensible reinforcements can result in a stiff reinforcing system similar to that obtained when relatively inextensible reinforcing elements are used.

The development of various types of facing presents another problem with the compressibility and flexural rigidity of the facing influencing both the stresses and the deformations within the reinforced soil structure and at its boundaries. It is possible, however, to utilise the various types of facing to control the deformations and stresses at the lateral boundary of the soil.

The complexity and difficulties involved in the development of appropriate models for the Limit State analysis of reinforced soil structures are recognized. However, the use of Limit State analysis of reinforced soil structures is seen to provide an opportunity to develop an integrated analytical approach which deals consistently with walls, slopes and embankments.

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