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Study of mechanisms and design methods of reinforcement in reinforced unpaved roads

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Abstract
Polymer grid or geotextile reinforcement may be used to improve the performance of reinforced fill layers placed on soft ground. This paper is concerned with the mechanics and design of reinforced unpaved roads built over soft clay which is a particular application of this reinforced soil technique. A discussion is given of the mechanics of reinforced unpaved roads for the case of a single application of a plane strain, monotonic, load and the design procedures that are currently available for this type of structure are reviewed. A new analytical design model is proposed. This new model is based on a membrane reinforcement mechanism and is appropriate for cases where large surface deformations are acceptable. Results obtained using these new models are shown to compare well with data obtained from previously published laboratory tests. The use of a finite element method to study this type of structure is described and the results of finite element analysis are used to discuss the accuracy of the proposed analytical model.

Keywords: reinforced pavement and geotextile reinforcement

Introduction

The structural performance of fill layers compacted over soft clay may often be substantially improved by placing a layer of geotextile or geogrid reinforcement on the surface of the clay prior to placement of the fill.

This reinforced soil technique is routinely used for a variety of applications including working platforms, parking areas and low cost unpaved haul roads. The various mechanisms of reinforcement that act in structures of this sort, however, are complex and not fully understood. Current design methods, particularly those that are based on assumptions about the mechanics of individual reinforcement mechanisms, are therefore considered to be not wholly satisfactory. In many applications of this type of construction, the surface of the fill layer is subjected to repeated loading caused, for example, by passing vehicles. It is generally found in practice that the deformations occurring in the reinforced unpaved road tend to increase in magnitude as the number of load applications increases. The mechanism of this repeated loading degradation is not fully understood, even for the more conventional case of unreinforced fill layers on soft clay. In view of this, many of the current design methods for reinforced fill layers are based on an approach in which the structure is analyzed for the case of a single load application with an empirical correlation used to deal with the effects of repeated loading.

Previous research on the analysis and design of reinforced unpaved roads has generally followed one of two broad approaches. One of these approaches is to use an analytical model to represent one, or more, of the reinforcement mechanisms that may be assumed to act within the system. This approach relies on the use of important assumptions about the nature of the mechanisms concerned and may result in significant modeling errors if these assumptions are incorrect or inaccurate. The models developed using this approach generally requires the specification of parameters relating to the assumed reinforcement mechanisms; appropriate values for these parameters may be difficult to determine in advance for a particular structure. Typical examples of design procedures developed using this general approach are the membrane analysis models proposed by Giroud and Noiray (1981) [9], Sellmeijer *et al*. (1982) [18] and Bourdeau (1989) [1], and the small deformation models proposed by Houlsby *el al*. (1989) [12], Milligan *et al* (1989) [16], Houlsby and Jewell (1990) [13] and Sellmeijer(1990) [19].

The second of these two broad approaches is to use a numerical method to formulate, and solve, the compatibility, equilibrium and constitutive equations for the complete system. This type of procedure is generally based on the use of a suitable finite element method. Although this class of calculation is often complex and lengthy to perform, this general approach has the important advantage that it is necessary only to specify the geometry of the structure and values of the appropriate material parameters. No assumptions are necessary about the detailed nature of the reinforcement mechanisms and appropriate material properties may be determined using suitable laboratory tests or empirical correlations. Typical analyses of this sort are described by Zeevaert (1980), Poran (1985), Burd, (1986) [3], Burd and Houlsby (1989) [12], Burd and Brocklehurst (1991) [6] and Brocklehurst (1993) [2]. It is important to note that in order to model successfully the large deformation mechanisms that are known to act in this type of system, it is necessary to base the finite element analysis on a suitable large deformation formulation. This adds a certain degree of complexity to the finite element equations and solution procedures, but is a feature that is available in several of the finite element programs that are currently available.

Although finite element analysis techniques are becoming more accessible to practicing engineers, practical design calculations are likely to continue to be based on the use of relatively simple analytical models of behaviour. Finite element solutions will continue to have significant value, however, in investigating the mechanisms that operate in reinforced soil systems of this type and in checking proposed design models.

The purpose of this paper is to discuss the reinforcement mechanisms that act in reinforced unpaved roads when a single monotonic load is applied. A new analytical model of a reinforced unpaved road deforming in plane strain is also proposed. This model is based on the analysis of a reinforcement mechanism that requires large geometry changes to occur to become mobilized. Design procedures based on this mode are therefore appropriate for cases where significant deformations are acceptable as, for example, might be the case in a temporary or low cost haul road. Although no attempt is made to develop a theory suitable for the case of repeated loading, this proposed model may be readily combined with existing empirical approaches (for example the procedures described by Giroud and Noiray (1981) [9] and De Groot (1986) [8] for the design of roads subjected to repetitive loads.

Mechanisms of reinforcement in reinforced unpaved roads

It is thought that the structural mechanisms that act in reinforced unpaved roads may be conveniently divided into two broad groups. One of these groups (referred to here as the group of 'small displacement mechanisms') does not require large geometric changes to occur within the structure in order to be mobilised. Reinforcement mechanisms in the second group, (described here as 'large displacement mechanisms') do, however, require significant structural displacements in order to become active. In addition to these two groups of mechanisms, geotextiles and geogrids may provide a useful separation function; this is particularly the case when the subgrade is very soft. This function is especially important in cases where the loading is repeated since it reduces the problem of subgrade degradation caused by the punching of individual fill particles into the clay.

One of the small displacement mechanisms that have been identified by previous workers is associated with the shear stresses that are induced at the base of the fill layer by a load applied to the fill surface. In an unreinforced unpaved road, the fill layer transmits shear stresses as well as normal stresses to the clay subgrade; these shear stresses tend to reduce the vertical bearing capacity of the subgrade. If a layer of reinforcement is placed at the base of the fill, however, then a proportion of these shear stresses are sustained directly by the reinforcement. This generates tensile forces in the reinforcement and a corresponding reduction in the outward acting shear stresses applied to the subgrade surface. The amount by which the shear stresses transmitted to the subgrade are reduced is thought to depend on the relative stiff nesses of the reinforcement and the surrounding soil. It has also been suggested by previous workers that the presence of reinforcement may improve the load- spread characteristics of the fill layer and that this may constitute another small displacement mechanism. There appears to be little evidence to support this suggestion, however.

The second broad group of mechanisms requires large deformations to occur before they become active. It is generally accepted that the most important of these large deformation mechanisms is associated with the membrane action of the reinforcement. This membrane mechanism is associated with the curvatures that develop within the reinforcement when the magnitude of the deformations becomes large. When tensile forces are present in the reinforcement and coincident with appreciable reinforcement curvature, then the normal stresses acting on each side of the reinforcement will be unequal. This effect tends to reduce the normal stresses transmitted to the subgrade immediately underneath the load with a consequential improvement in the capacity of the road. The reinforcement curvatures may also tend to provide additional vertical stresses to the surface of the clay in the area immediately outside of the loaded area. This has the effect of increasing the bearing capacity of the clay in the area beneath the load thus providing further improvement.

Design Methods

One of the earliest design methods for reinforced unpaved roads in which an attempt was made to develop a detailed model of the interaction between the reinforcement and the soil was proposed by Giroud and Noiray (1981) [9]. Although this model is based on assumptions that simplify the behaviour of the system, it has been most successful in stimulating interest in design methods for this type of structure and is extensively cited in later work. This design model, which is based on the analysis of a membrane reinforcement mechanism, deals with the interaction that occurs between two wheel loads and makes the implicit assumption that the clay subgrade behaves in a rigid-perfectly plastic manner. The reinforcement is assumed to be a linearly elastic sheet of material placed at the base of the fill.

The Giroud and Noiray method, in common with most of the other proposed analytical models of this type of structure, makes use of a simple load-spread mechanism for the fill in which load applied at the surface is assumed to be uniformly distributed over an area at the fill base defined by a load-spread angle, P **(**Fig. 1).

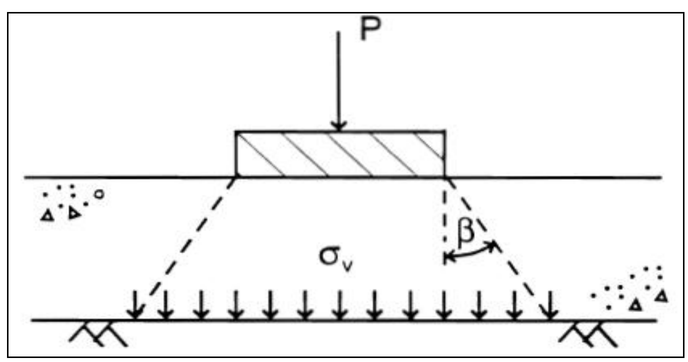

Fig 1: Load Spread Within the fill layer.

In this type of approach, the value of P needs to be specified at the start of the analysis. It is unfortunately the case that the result of any prediction made using this type of load-spread model is sensitive to the value of P that is adopted and yet it is often unclear how an appropriate value of A should be chosen for a particular application. It is clearly to be expected that an appropriate value of P will depend on the quality of the fill itself. There is some evidence to suggest (for example the results presented by Meyerhof (1974) [15], the laboratory studies described by Love (1984) [13] and Love *et al* (1987) [13] and finite element studies discussed by Brocklehurst (1993) [2], however, that the strength of the clay may also have an important influence on the mechanism of load-spread within the fill layer with the magnitude of P tending to be greater for soft than firm clays.

In the Giroud and Noiray (1981) [9] design method, the shape of the reinforcement is approximated by three parabolas as shown in Fig. 2

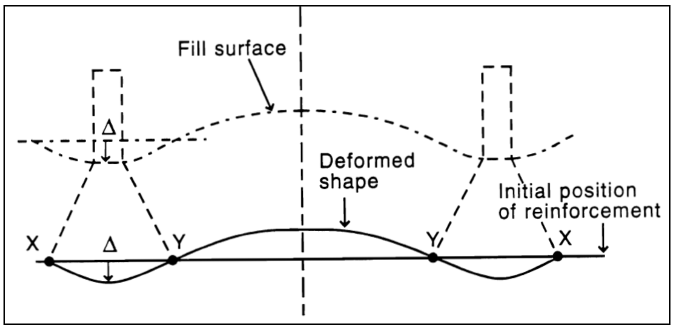

Fig 2: Deformed shaped of reinforcement

Where, the points of zero vertical displacement (points X and Y) correspond to the edges of the loaded area at the base of the fill. The displacement of the wheel at the fill surface is assumed to be equal to the displacement of the reinforcement immediately beneath the wheel center-line, A. The mean reinforcement strain, corresponding to a particular value of A, is obtained from geometrical considerations by making certain assumptions about the fixity of the reinforcement at points X and Y. Finally, the contribution of the reinforcement force to the strength of the system is assessed by considering the equilibrium of the portion of reinforcement immediately beneath the wheels. The assumptions made about reinforcement fixity in this method lead to a model that may predict an excessively stiff response (Burd 1986) [3], particularly for the case of stiff reinforcement and large rut depths.

Several other analyses of membrane mechanisms of reinforcement have been proposed. Sowers *et al* (1982) [20], for example, suggest a method of analysis for a single wheel that is in many respects similar to that of Giroud and Noiray (1981) [9]. Sellmeijer *et al*. (1982) [18] propose an alternative approach in which a set of normal stresses acting at the reinforcement interface is assumed and membrane equations formulated and solved to obtain the corresponding deformed shape. The reinforcement boundary condition adopted in this case is zero horizontal displacement at the edge of the road. While this boundary condition may be appropriate if the reinforcement is indeed pinned at the road edge, it may in other cases lead to a spurious predicted dependence of performance on the width of the structure.

The model of membrane action described by Bourdeau (1989) [1] represents an important development in the analysis of this type of system. In this model, an assumed set of stresses is applied to the reinforcement and a solution is obtained to the appropriate membrane equations. This approach differs from that of Sell-Meijer *et al* (1982) [18] in the important respect that the soil is assumed to apply shear stresses to the reinforcement in addition to normal stresses. This leads to the possibility of the use of a compatibility condition in which the change of reinforcement length associated with gross geometry changes is equated to the reinforcement extension caused by the assumed shear stresses acting at the soil-reinforcement interface. This compatibility condition avoids the need to choose an arbitrary boundary condition for the reinforcement tension and therefore removes one of the main difficulties of the earlier methods. This particular model, however, is developed specifically for the case of an elastic subgrade and might, for example, be suitable to model the behaviour of reinforced fill layers on peat. The assumptions adopted in this model lead to a relatively complex set of equations that require the use of a numerical method in order to obtain a solution.

Few authors have proposed design models based on small displacement mechanisms of behaviour. One model of this sort, however, is described by Houlsby *et al*. (1989) [12] and Milligan *et al*. (1989) [16] for a plane strain analysis and by Houlsby and Jewell (1990) [13] for an axisymmetric geometry. The broad assumptions on which this model is based are illustrated in Fig. 4 for the case of a single footing applied to the fill surface. If a load is applied to the footing, then the corresponding vertical stresses, av, at the surface of the subgrade are assumed to be distributed according to a conventional load-spread mechanism. The fill immediately beneath the footing is assumed to be in a state of active failure and the fill immediately adjacent to the footing is assumed to be in a passive failure state. Equilibrium considerations are used to evaluate the value of the resulting shear stress, z f thatis developed at the base of the fill. In the unreinforced case (Fig: 3(a)),

Fig 3: Shear Stress Mechanisms (after Houlsby *et al*. 1989) [12]

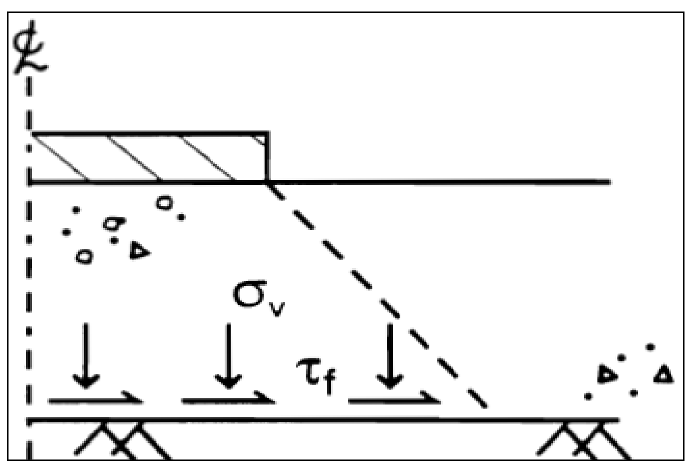

Fig 3: (a) Unreinforced

The magnitude of av necessary to cause failure is calculated using plasticity solutions in which the tendency of the outward acting shear stress to reduce the subgrade bearing capacity is included. In the reinforced case (Fig. (3(b)),

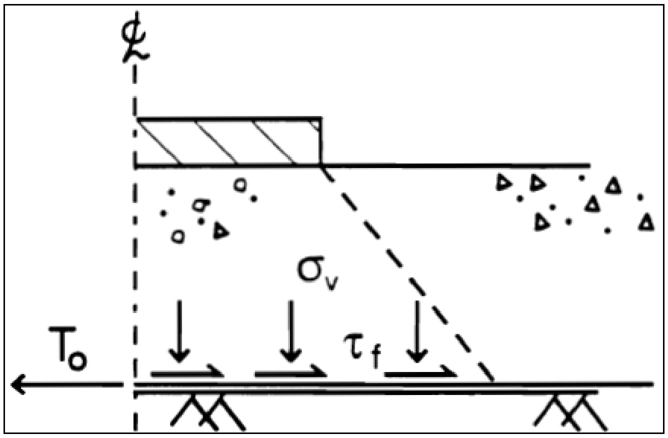

Fig 3: (b) Reinforced

The shear stresses at the base of the fill are assumed to be sustained by the reinforcement and the shear stresses applied to the clay surface are assumed to be zero. It is possible in this case to estimate the value of reinforcement force, T., acting on the footing Center-line by considering horizontal equilibrium of the reinforcement.

Conclusions

Current design methods for reinforced granular layers on soft clay are generally based on relatively simple analytical models of behaviour. Whilst these models are convenient for design they do not always reflect accurately the reinforcement mechanisms that act in this type of system. Finite element methods may be used to perform detailed analyses of this type of structure; these calculations tend to be expensive and time-consuming to perform, however and not appropriate for routine design. It is suggested that the design of this type of reinforced soil structure will continue to be based on the use of simple analytical models of behaviour.

An analytical model of a plane strain membrane mechanism of reinforcement is described in the paper. This model is intended for use in routine design calculations and leads to equations that are relatively simple to manipulate. The model is shown to provide a reasonable fit with previous model test data and also the results of finite element analysis although some features of performance, for example elastic soil deformations and shear stresses developed at the base of the fill immediately beneath the load, are not modeled well. Finite element methods remain the most appropriate theoretical approach to obtaining high quality information about the behaviour of reinforced unpaved roads although these calculations tend to be difficult and expensive to perform. The finite element analysis described in this paper illustrates well the tendency of the reinforcement to reduce the magnitude of the shear stresses transmitted to the subgrade and also the membrane mechanism that becomes increasingly important at large deformations.

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