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Steel reinforced embankments on soft clay foundations

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The results of finite element analyses are used to examine the behaviour of steel strip reinforced embankments constructed on soft clay foundations. Some results are presented which illustrate that the mode of failure and degree of improvement in embankment stability may vary substantially depending on the amount of reinforcement used and the properties of the foundation soil. The use of partial factors and definition of failure of a reinforced embankment system are discussed in the context of using limit state design.

1 INTRODUCTION

The past several years have seen a dramatic increase in the use of reinforcement as a means of ensuring the stability of embankments constructed on soft foundations. Common reinforcement materials used include; geotextiles, geogrids, steel meshes and steel strips (Rowe and Soderman, 1984; Lockett and Mattox, 1987; Fowler et al., 1986; Elias and Johnson, 1982 and others).

The objective of this paper is to discuss the use of steel strips as reinforcement for granular embankments constructed on soft clay foundations which do not exhibit strain softening. Results of finite element analyses will be examined. Details regarding the numerical model which was used are discussed by Rowe and Mylleville, 1988.

2 PARAMETERS CONSIDERED IN THE NUMERICAL MODEL

When constructing embankments on soft clay foundations, the most critical situation generally corresponds to that at the end of construction. In order to predict the short term behaviour of embankments on relatively soft cohesive soils, the undrained shear strength c_u (ϕ=0) and undrained modulus E_u (taking Poisson's ratio to be 0.48) were used. Figure 1 shows the general arrangement which was adopted in the finite element analyses. The results examined herein are for the case of a soft clay deposit with strength and modulus which increase linearly with depth from some surface value. This type of strength profile is commonly encountered in soft, normally or slightly overconsolidated clays.

Soft clay deposits of depth, D, equal to 7.5 m and 15 m were examined and assumed to be underlain by a rigid base. The ratio of undrained modulus, E_u, to undrained strength, c_u, considered was E_u/c_u=125. The unit weight, γ, of the clay was assumed to be 16.5 kN/m³, and the coefficient of earth pressure at rest was taken to be K_o'=0.60.

The value of unit weight adopted for the embankment fill was 20 kN/m³ and the angle of internal friction used was ϕ=36°.

The steel reinforcement used was in the form of Reinforced Earth (R) (eg. Vidal 1968) ribbed steel strips, of thickness, t=5 mm and width, w=50 mm (see Figure 1). The strips used have a yield strength of 350 MPa and an ultimate tensile strength of 490 MPa. Centre to

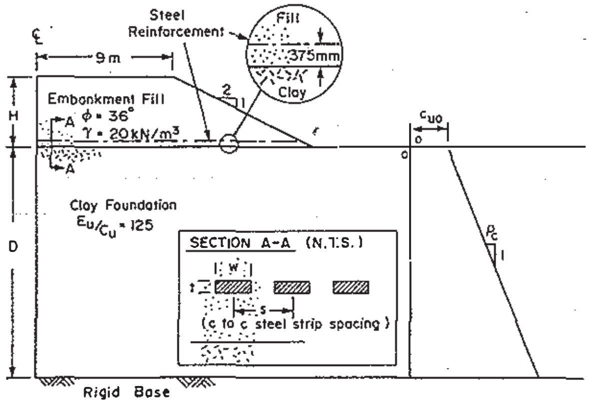

Figure 1. General Arrangement

centre spacings, S, of 375 mm and 125 mm were examined, with the strips being placed transverse to the alignment of the embankment (see Figure 1). The strips were located entirely within the embankment fill at a distance of 375 mm above the clay/fill interface in order to develop frictional resistance on both faces of the reinforcement.

3 DEFINITION OF FAILURE AND THE USE OF PARTIAL FACTORS

For purposes of further discussion, the practical definition of failure of the reinforced embankment is the height at which the increment in vertical displacement is equal to or exceeds the increment in fill thickness added. The addition of more fill will not result in a net increase in embankment height. For heavily reinforced embankments, as is the case when using steel strip reinforcement, this practical definition of failure height is in fact very close to the plasticity collapse height at which point uncontained plastic flow occurs.

The cases which are going to be discussed were analyzed using a limit state type design philosophy, where strength parameters are factored down and loads are factored up. The partial factors used were taken from the Ontario Highway Bridge Design Code, 1983. For example, a factor of 0.65 was applied to the clay foundation strength parameters and factors of 0.8 and 1.25 were applied to the tangent of the angle of internal friction and unit weight of the fill respectively. For the various cases presented herein, the clay foundation strengths quoted are nominal (unfactored) values.

Collapse of a reinforced embankment on a soft clay foundation may in many instances be preceded by yield in the reinforcement. After the onset of first yield, additional fill can be added prior to collapse of the entire reinforced embankment system.

In some instances, the amount of fill that can be added after first yield up to collapse is significant. Figures 2 and 3 show results for a reinforced embankment with a steel spacing of 125 mm, constructed on a clay foundation of depth, D=15 m. The nominal foundation strength parameters are c_{uo}=30 kPa at the surface and a rate of increase in strength with depth of ρc=2.5 kPa/m.

The extent of plasticity at the occurrence of first yield in the reinforcement is shown in Figure 2, where the cross-hatched portion in the clay foundation and embankment fill is that zone of soil which has reached its shear strength. The stiff reinforcement has limited the extent of yield in both the fill and foundation up to this point. The failure in the foundation is contained by a large region of elastic soil and hence the embankment is still stable. Following first yield of the reinforcement, an additional 1.9 m of fill was added before failure of the entire embankment system occurred. This represents an additional 30% increase in fill thickness beyond the point of first yield in the reinforcement. Figure 3 shows the plastic region for the embankment at failure.

Cases such as the one just discussed raise an important point with regards to what one defines as failure of the reinforced soil system. In using limit state design (ie. where partial factors are applied to strengths and loads), it is too conservative to associate the embankment height required to cause first yield with the failure height of the embankment. It is more realistic to define the failure height as the height at which the entire embankment system fails.

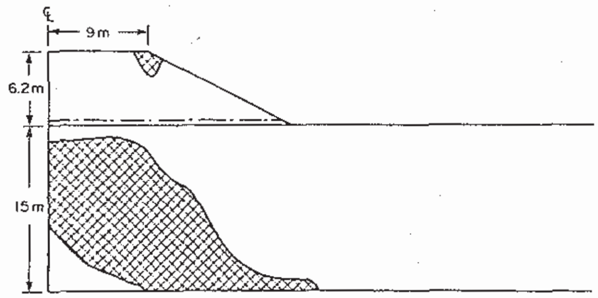

Figure 2. Plastic region at first yield of reinforcement for nominal parameters c_{uo}=30 kPa, ρ_c=2.5 kPa/m, S=125 mm and D=15 m

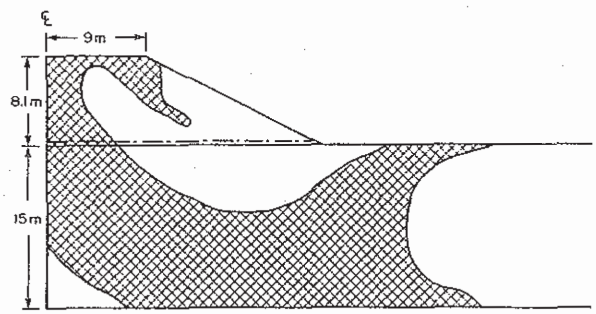

Figure 3. Plastic region at failure for nominal parameters c_{uo}=30 kPa, ρ_c=2.5 kPa/m, S=125 mm and D=15 m

4 BEHAVIOUR OF SOME STEEL REINFORCED EMBANKMENTS

The amount of steel strip reinforcement used in an embankment may have a definite effect on the failure mechanism, depending on the nature of the clay foundation.

Figure 4 shows the plastic region and velocity field for an 18 m crest width embankment constructed on a 7.5 m deep clay foundation with a nominal (unfactored) undrained shear strength at the surface of c_{uo}=15 kPa and a rate of increase with depth of ρ_c=2.5 kPa/m. For a steel strip spacing of S=375 mm, the calculated failure height was 4.4 m. Having adopted a limit state philosophy in the analysis, the failure height obtained using factored parameters corresponds to the allowable working height for the nominal (unfactored) conditions. The unreinforced failure height is 2.8 m, thus a steel strip spacing of 375 mm gives rise to a 57% increase in the allowable height to which the embankment could be constructed on this deposit. The velocity field is also shown in Figure 4. The arrows indicate the direction and relative magnitude of movement in the soil at the onset of failure. Careful examination reveals an extensive lateral component to the deformation of both the fill and foundation soil. In this case, the failure mechanism is a function of yield in the reinforcement, some reinforcement pullout and general foundation failure.

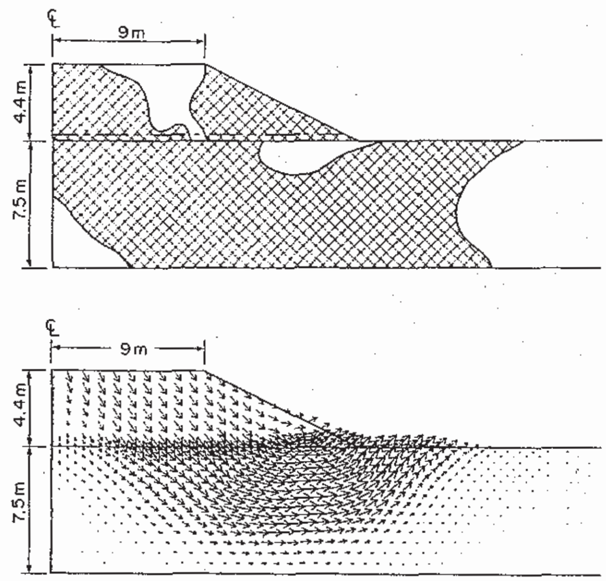

Figure 4. Plastic region and velocity field at failure for nominal parameters c_{uo}=15 kPa, ρ_c=2.5 kPa/m, S=375 mm and D=7.5 m

The effect of increasing the amount of reinforcement by a factor of three (ie. adopting a closer strip spacing) can be seen in Figure 5. The clay foundation has the same properties as the case just discussed. A steel strip spacing of S=125 mm increased the failure height to 5.0 m which corresponds to an 80% improvement over the unreinforced case. The increased amount of steel has also prevented yield of the reinforcement. In this case, the failure mechanism is a function of general foundation failure and some strip pullout.

A three-fold increase in the amount of reinforcement has improved the embankment performance significantly and as one might expect, resulted in an increase in the failure height. It should however be noted that the more heavily reinforced embankment (ie. S=125 mm) is approaching the maximum height which can be achieved for a perfectly reinforced embankment. Adopting a strip spacing closer than 125 mm is unlikely to achieve significant additional improvement in failure height for the foundation conditions examined.

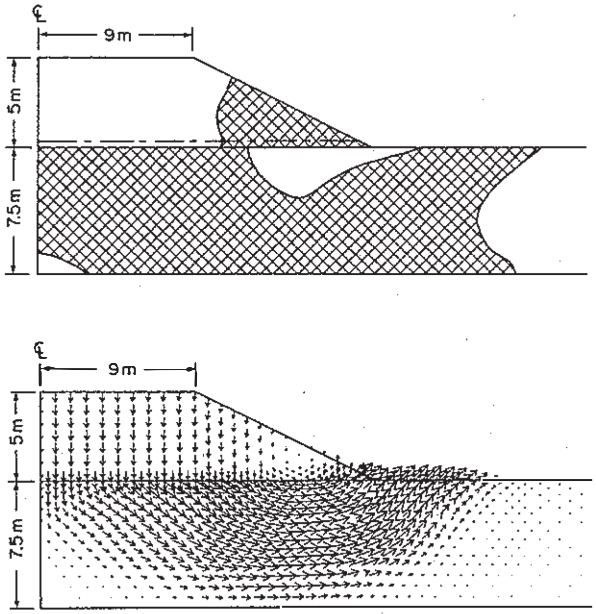

Figure 5. Plastic region and velocity field for nominal parameters c_{uo}=15 kPa, ρ_c=2.5 kPa/m, S=125 mm and D=7.5 m

There are some important differences in the failure mechanism for the more heavily reinforced case (ie. S=125 mm) compared to the embankment constructed with a strip spacing of 375 mm. Examination of the velocity field in Figure 5 reveals that there is essentially no lateral component of displacement in the embankment fill. Looking at the plastic region, there is no plasticity in the same area. This would suggest that the more heavily reinforced embankment moves downward as a rigid block over a width of approximately 30 m in this case.

The point about which rotation appears to be occurring in the fill (ie. the edge of an approximate rigid footing) corresponds to that point where the applied pressure γh equals the surface bearing capacity of $5.14c_{uo}$ when factored values of γ and c_{uo} are considered. This provides some additional evidence for an approximate method one might use to estimate collapse heights for heavily reinforced embankments proposed by Rowe and Soderman (1987). Based on the bearing capacity considerations of an idealized rigid footing of equivalent width, it provides one with a means of determining the maximum benefit that can be achieved by reinforcing an embankment. Keeping in mind that a reinforced embankment cannot be reinforced beyond being rigid, the simple approach proposed by Rowe and Soderman, provides the designer with an assessment as to whether a given height requirement can be satisfied.

The effect of ρ_c, the rate of increase in strength with depth in the clay foundation, on the failure mechanism in the underlying foundation can be seen if one compares the results shown in Figures 6 and 7. Figure 6 shows the velocity field at failure for an embankment with a steel strip spacing, S=125 mm, constructed on a clay foundation with a nominal undrained shear strength at the surface of c_{uo}=22.5 kPa and a rate of increase with depth of ρ_c=2.5 kPa/m. The failure mechanism in this case extends to a depth of approximately 10 m. Figure 7 is the velocity field at failure for the

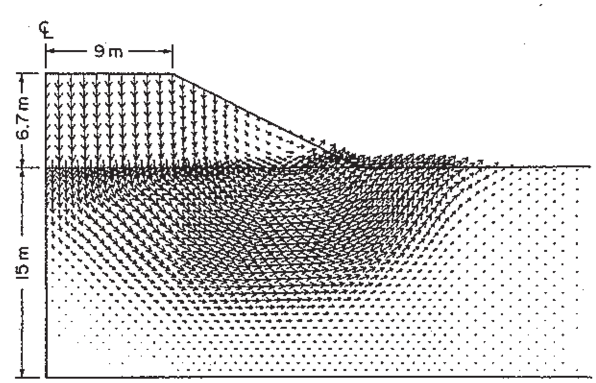

Figure 6. Velocity field at failure for nominal parameters c_{uo}=22.5 kPa, ρ_c=2.5 kPa/m, S=125 mm and D=15 m

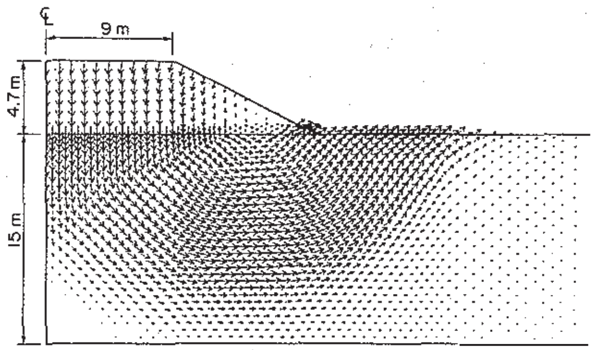

Figure 7. Velocity field at failure for nominal parameters c_{uo}=22.5 kPa, ρ_c=1 kPa/m, S=125 mm and D=15m

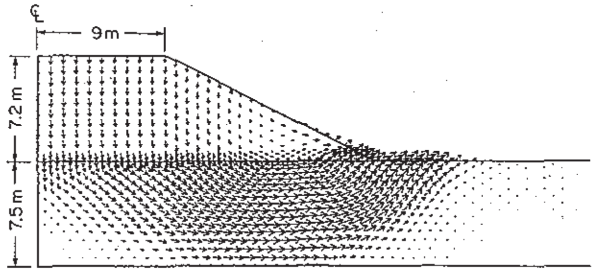

Figure 8. Velocity field at failure for nominal parameters c_{uo}=22.5 kPa, ρ_c=2.5 kPa/m, S=125 mm and D=7.5 m

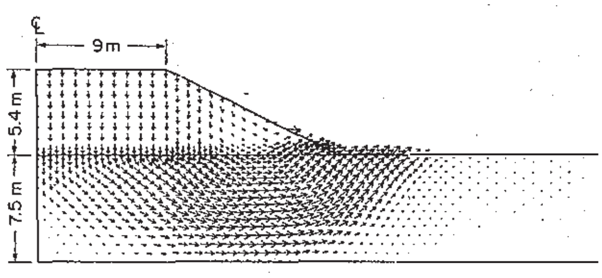

Figure 9. Velocity field at failure for nominal parameters c_{uo}=22.5 kPa, ρ_c=1 kPa/m, S=125 mm and D=7.5 m

same steel spacing and nominal parameters except that the rate of increase in strength in the clay foundation is lower, namely ρ_c=1 kPa/m. Comparing this velocity field with the previous case, one can observe that the failure mechanism extends deeper into the foundation, to a depth of about 12.5 m and encompasses a larger region of the foundation soil.

Having seen that the rate of strength increase with depth in the clay foundation effects on the depth of the failure mechanism, one would expect that a rigid base at depth might also influence the overall embankment performance. The velocity field shown in Figure 8 is for an analysis performed using the same nominal parameters as for the case shown in Figure 6, except that now the depth of the deposit (or depth to a rigid base) is reduced to D=7.5 m. The result being an increase of about 7% above the failure height obtained for the case of D=15 m, if one considers a value of ρ_c=2.5 kPa/m in the clay foundation. Similarly, the velocity field in Figure 9 is for D=7.5 m and the same parameters used for the analysis reported in Figure 7. For a value of ρ_c=1 kPa/m, reducing the depth to a rigid base by half has resulted in a 15% increase in the failure height when compared to the failure height for D=15 m. In summary, the effect of depth to a rigid base is more significant for a lower ρ_c value, where the failure mechanism extends deeper into the underlying clay foundation.

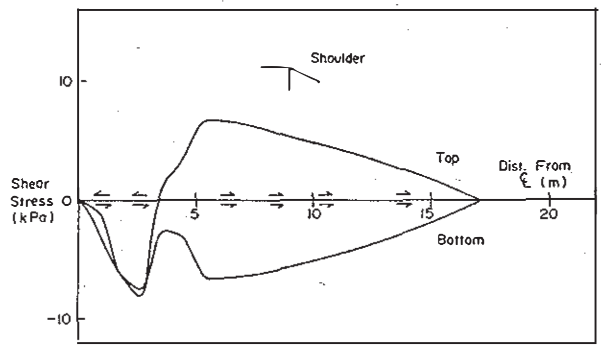

Figure 10. Distribution of shear stress along reinforcement at failure for nominal pararmeters c_{uo}=15 kPa, ρc=2.5 kPa/m, S=375 mm and D=7.5 m

The shear stress distribution above and below the reinforcing strips obtained from finite element analysis for the case of c_{uo}=15 kPa, ρ_c=2.5 kPa/m, S=375 mm and D=7.5 m is shown in Figure 10. The distribution is per metre width of embankment and corresponds to the point at which failure of the embankment occurs. The central 6 m of reinforcement is subjected to direct shear whereas the remainder of the reinforcement experiences "pullout" type shear. At failure, pullout is only occurring along the outer 9 m of the reinforcement (ie. between the shoulder and toe of the embankment).

5 CONCLUSIONS

The results of finite element analyses have been used to illustrate the behaviour of steel reinforced embankments on soft clay deposits. Steel strip reinforcement can substantially improve the stability of granular embankments constructed on soft clay deposits where the undrained shear strength increases with depth.

The performance of these embankments is highly dependent on soil-structure interaction between the foundation, the embankment fill and steel strip reinforcement. It has been demonstrated that the failure mode for steel reinforced embankments on soft clay foundations may vary substantially depending on the amount of reinforcement used and the properties of the underlying foundation soil.

It has been shown that in some instances, yield of the reinforcement may occur well before collapse of the entire embankment system. It has been suggested that when using limit state design for reinforced soil systems, failure should be associated with failure of the entire system rather than a component of the system, such as the steel.

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