Stability calculation of reinforced soil slope
Le calcul de stabilité des pentes renforcées

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SYNOPSIS Limit equilibrium method of slices is recommended for reinforced soil slope stability calculation. The effect of reinforcing element is taken into account as the additional horizontal interslice force ΔQ. The value of the design horizontal force Q of geotextile is discussed in relation to the rheology, the limit state of serviceability and soil deformation. There are presented some results of the comparative calculations.

INTRODUCTION

The importance of the reinforcing geotextiles on soil slope stability improvement was proved in many cases both by the laboratory research (e.g. Ovesen and Krarup 1983, Vaníček 1983 a) or by the practical application (e.g. Vaníček 1983 b). The development of soil slope reinforcement is in practice closely connected with the need of the simple method for slope stability calculation and also with the question of the input parameters of soils and geotextiles selected for this method. The basic questions are discussed with the connection of these problems.

METHODS OF SLOPE STABILITY CALCULATION

At present it is generally accepted that for the soil embankment design the following limit states should be satisfied:

- ultimate limit states
- serviceability limit states.

In the first case the slope stability failure is mostly crucial while in the second case it is the deformations of the embankment or slope which cause loss of serviceability of structures, roads or services sited on or near the embankment or slope.

The finite element method is now prefered from the analytical and numerical methods for the fullfilment of the serviceability limit states. But their usage is not common in general cases and the credibility is limited by the difficulty of evaluating the parameters that govern the stress-strain behaviour of the material from the results of field or laboratory tests. Some publications, e.g. Andrawes et al (1982), Petrík, Baslík, Leitner (1982) show on the difficulties of this approach for reinforced soil.

By our opinion it is possible in general practice to give the preferability to the limit equilibrium method of slices as it is still in cases of the unreinforced soil slopes. But it would be usefull to support this method by additional conditions which would partly cover the limit states of serviceability.

From the different methods of slices (e.g. Bishop, Morgenstern-Price, Sarma) our activity was concentrated on Janbu´s method - Janbu (1973). The advantages of this method are as follow:

- general shape of the slip surface
- interslice forces are taken into account
- typical iterative method which is appropriate for microcomputers
- horizontal force increase ΔQ between individual slices can be taken as an additional force from reinforcement.

Last point is very important because it is connected with our approach to the question how to take into account the reinforcing effect. Horizontal force from the reinforcing element is prefered for example by Brandl (1983). The distribution of this horizontal tensile force along reinforcing element can have general character - e.g. Broms (1977). In our calculation we decided for linear distribution of this horizontal force with the maximum in the intersection with potential sliding surface - fig. 1. The anchoring lenght l_k can be checked through this assumption also.

Some difficulties associated with the limit equilibrium method of slices were discussed by Ching and Fredlung (1983). The main difficulties are associated with

- the inclination of the slip surface
- soils where the cohesive component dominates the shear strenght
- the point of the application of the interslice forces

First aspect has main importance, because

- cohesion of the compacted soils is usually a low one
- placing of the point of application of the interslice forces into centre of the slice height

is reasonable in most cases.

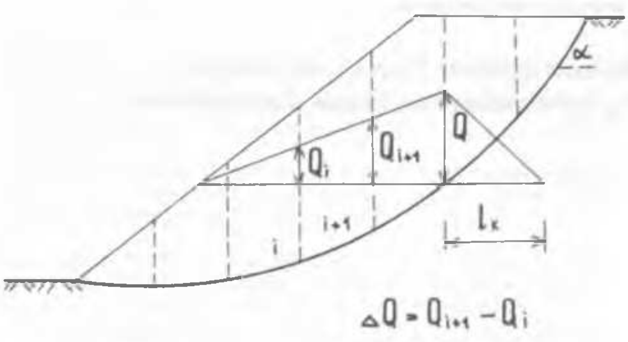

Fig. 1 Linear distribution of tensile force along reinforcing element

We get slow or zero convergency when the angle α between slip surface and horizontal line is a great one. Usually - according to Ching and Fredlund - the condition $\alpha \leq 45 + \varphi/2$ must be fulfilled for active zone resp. $\alpha \leq 45 - \varphi/2$ for passive zone.

During the testing of Janbu´s method we have prepared subprogram for finding out the most dangerous slip surface which is composed by broken line.

CLAIMS ON GEOTEXTILE

The design efficiency is strongly influenced by right selection between different types of the geotextiles. Therefore it is usefull to summarize basic cases with their differences together with all factors which have influences on input parameters for stability calculation.

Basic cases of soil reinforcement

Three basic cases of soil reinforcement are schematically shown on fig. 2

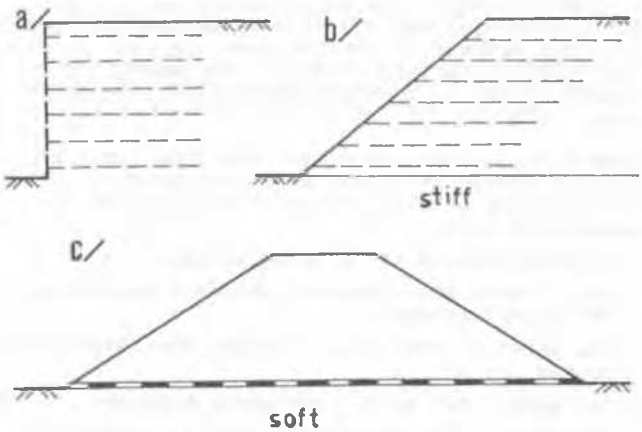

Fig. 2 Three basic cases of soil reinforcement

Case a) - retaining wall

- factor of safety F along potential sliding surface without reinforcement is usually less than 1
- potential sliding surface is going through soil backfill where the difference between the rezidual shear strength τ_r and the maximum shear strength τ_f is relatively small one.

Case b) - soil embankment on the stiff basement

- factor of safety without reinforcement is roughly 1, more often F = 1.0-1.2.
- the difference between τ_r and τ_f is also small one.

Case c) - soil embankment on the soft basement

- factor of safety without reinforcement is usually less than 1
- potential sliding surface is going through the soft basement where the difference between τ_f and τ_r can be significant.

In the case b) the geotextile is used mainly as a supplementary element which has to increase the factor of safety F to the claimed value, usually F = 1.5. It means that for limit equilibrium state the certain tensile strength in the geotextile is mobilized while in soil the maximum shear strength was not reached. In the case of local failure in soil which is connected with the small decrease in shear strength the geotextile is able to increase the tensile strength.

In two other cases the geotextile is a main bearing element. The demands on such geotextiles are higher one, especially on higher stiffness - - quicker mobilization of the tensile force and higher maximum tensile strength.

Further more attention will be given to the basic case b). For this case schematic working diagram is shown on the fig. 3.Dash line represents the working diagram for the geotextile which was prestressed. This prestressing can help to the quicker mobilization of the tensile force in the geotextile.

The design value of the tensile force Q for the geotextile

Tensile test

For obtaining of the working diagram of the geotextile we are performing the unconfined tensile test on the sample with the width 200 mm and length 100 mm as recommended by McGown et al (1981). This test can be easily performed by the textile industry and the results can be part of the certificate of this geotextile. We are using the term quick test, because the loading increase is applied very quickly - up to 1 minutes to the failure.

For the general purposes it is not necessary to perform special tensile test on the geotextile which is confined by soil and laterally loaded because

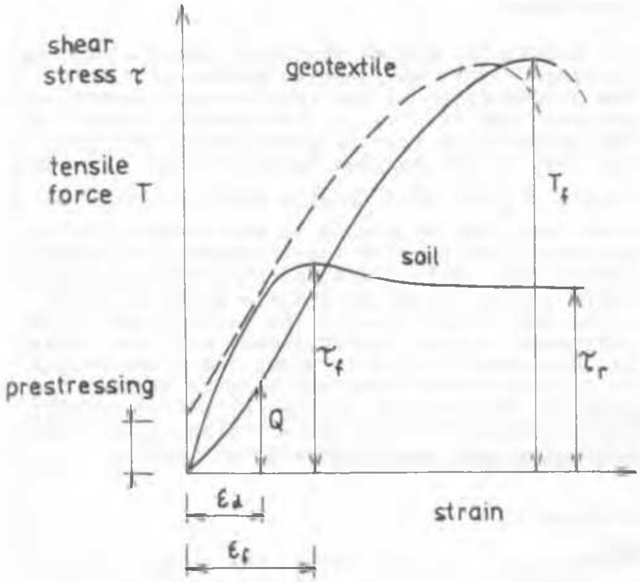

Fig. 3 Working diagram for soil and geotextile

- we are on the safe side
- the differences in the results for woven geotextiles (which are used in most cases for reinforcement) under different conditions of testing are not so significant - McGown et al (1981 b), Christopher, Holtz and Bell (1986).

Rheological aspect

The design value Q is strongly influenced by its ratio to the maximum tensile force at failure T_f. The geotextiles are mostly manufactured from polymers (polyamide, polypropylene, polyester) which have significant rheological behaviours with time

- the deformation is increasing for constant loading, or
- the relaxation of stresses is taking place for constant deformation.

The interesting results in this direction are presented by Baslík (1987). He measured the deformation of the individual fibres with time for constant loading. For ratio Q/T_f = 0.5 the failure of polyamide or polyester fibres occurs after 20 or 80 days. For polypropylene the results are shown on fig. 4. For the elimination of the reological aspect we recommend ratio $Q/T_f \leq 0.25$.

The situation will be more favourable for our basic case b), because surrouding soil can soften this rheological aspect. On the other side this phenomenon deserves more attention for the cases of the retaining walls or for reinforcement of the contact between fill and soft basement.

Further aspects which can have the influence on the ratio Q/T_f are

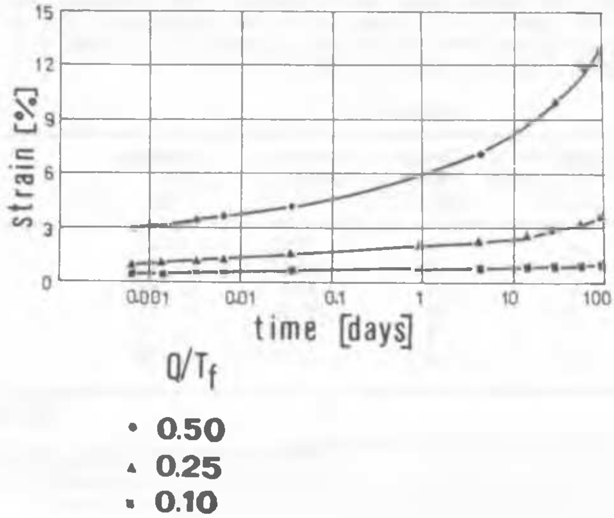

Fig. 4 Long term tensile tests of the polypropylene fibres for the different levels of loading.

- lifetime of the soil reinforced construction
- cyclic loading - for example by traffic on the top of the embankment.

Time effect can be also influenced in the positive direction, for example by the shear strength increase due to the pore pressure dissipation.

The design value of the tensile force Q for the geotextile can also be limited by acceptable value of axial strain ε_d. It is not only the supplementary condition for the serviceability limit states but also the condition which explains a certain relationship between ε_d and ε_f (strain for shear failure of given soil). Usually we do not want to overcome shear failure of soil. For basic cases we recommend ε_d = 5%, for important long term construction roughly 2-3% and for short term construction which is not sensitive to the differential settlement the value ε_d can be 7-8%. From the last two conditions mentioned above the stricker one will be decisive.

COMPARATIVE CALCULATIONS

Homogenious slope

As a basic case we took slope with the height H=10 m and the inclination 1:1.5 and with the following soil parameters: $\varphi_{ef}=30^0$, c_{ef}= 6 kPa. Firstly we calculated the factor of safety along the most dangerous circular slip surface without the reinforcement - F_0=1.1826. After that we observed the increase in this factor of safety if only one layer of reinforcement was put into constructed embankment. The results are summarized in table I, where d is the height of the reinforcing layer from the basement. For regular reinforcement - 7 layers with the distance 1.25 m we obtained the factor of safety F = 1.5839, it means the increase of 33.93%

TABLE I

Situation of reinf. layer d (m)	Design value Q ($kN.m^{-1}$)	Factor of safety F	Increase in F (%)
2	8	1.2262	3.69
4	8	1.2487	5.59
4	16	1.3157	11.25
4	24	1.3926	17.76
6	8	1.2191	3.09
8	8	1.2179	2.98

Slope with strip foundation

By Janbu's method it is possible to calculate the bearing capacity of strip foundation and most dangerous slip surface. For the situation on fig. 5 we obtained the bearing capacity q_u = = 750 kPa. After that we used regular reinforcement and calculated the factor of safety F as a function of the design value Q for the geotextile reinforcement. For soil with the high shear strength and highly loaded footing we need higher design value Q.

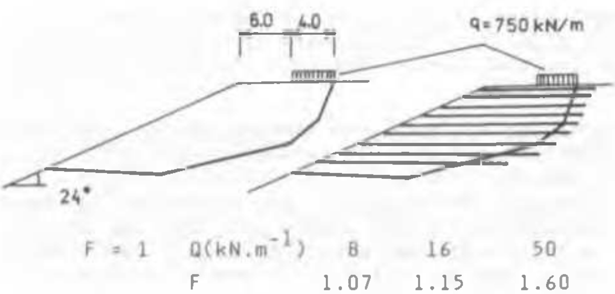

Fig. 5 Scheme of the slope with strip foundation

Embankment for the new tram line

Slope inclination 1:1.5 was claimed for the construction of a new line with the embankment height H = 10 m. The shear parameters of this fill were in the range: c_{ef}= 5-10 kPa, φ_{ef} = = 22-25^0. The external loading was 156 kN on one leading axle (for the dynamic coefficient 1.2).

For the slope without the reinforcement and with best value of the shear parameters (c_{ef}=10 kPa, φ_{ef}=25^0) the factor of safety F is 1.18. Therefore we recommended regular reinforcement (9 layers) and for the real value c_{ef}=5 kPa, φ_{ef}= = 25^0 we got the factor of safety F = 1.77 for the design value Q = 15 $kN.m^{-1}$. For the slip surface going behind second rail F = 1.78. For the recommended reinforcement and worst shear parameters the factor of safety is still higher than 1.5 (F = 1.57).

CONCLUSION

For reinforced slopes stability computations we recommend limit equilibrium method of slices. The introduction of the reinforcing element is obvious from the fig. 1. The design value Q for the geotextiles from polymers should be less than 25% of the maximum tensile force T_f or the strain ε_d for this tensile force Q should be less than 2-8% according to the construction importance. The regular reinforcement is probably better than small number of reinforcing layers, where most critical slip surface can go above or behind of the zone of the reinforcement. We recommend regular reinforcement with the vertical distance H/6 - H/16 along the slope height. It is also better from the surface erosion point of view. Recommended design value Q is roughly in the range of 8 - 50 $kN.m^{-1}$ with higher value for the slopes with the external loading.

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