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Analysis of a slope reinforced with rockbolts

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ABSTRACT: The stress on a cut slope reinforced with rockbolts was analysed under the finite element method (FEM). In the stress field analysed, the opimization technique was employed in an attempt to find the minimum safety factor of a slip line. In comparison with a slip line examined on an unreinforced slope the slip line on the reinforced slope was deeper in the slope and had a higher safety factor.

1 INTRODUCTION

Many studies have been made on the use of rockbolts to reinforce slopes. However, the mechanics of this type of reinforcement are not totally clear. While there is still uncertainty on many points, the authors believe that the following explanation can be made.

Due to the release of stress when earth is excavated from the face of a slope the ground around the excavated surface deforms laterally. The lateral stress in the ground becomes less than it was before the excavation. Therefore, the resulting stress value on the new slope reaches Coulomb's failure criterion (Fig.1a).

When rockbolts are used to reinforce a newly excavated surface, the ground near the bolts is confined by them and does not easily deform. The result is that the decrease in lateral stress in the ground is less than it is without reinforcement and the stress value does not reach Coulomb's failure criterion (Fig.1b).

This is important in the design of rockbolt reinforced slopes. At present, however, it receives little attention during the design stage. FEM analysis can be used in predicting stress but the data obtained is incomplete. What is required is information concerning the safety factor of the slip line.

In this paper the optimization technique is applied to the stress data obtained through FEM analysis in order to find the slip line having the minimum safety factor.

2 PROCEDURE FOR SLIP LINE SEARCH

In this paper we use the same procedure as Yamagami (1984) to determine the slip lines in the ground under the footing. This is as follows.

The safety factor of a slip line in a given slope (Fig.2) is defined in the following equation using Coulomb's failure criterion.

$$F_s = \frac{\int_s (C + \sigma \cdot \tan\phi) \cdot d_s}{\int_s \tau \cdot d_s} \qquad (1)$$

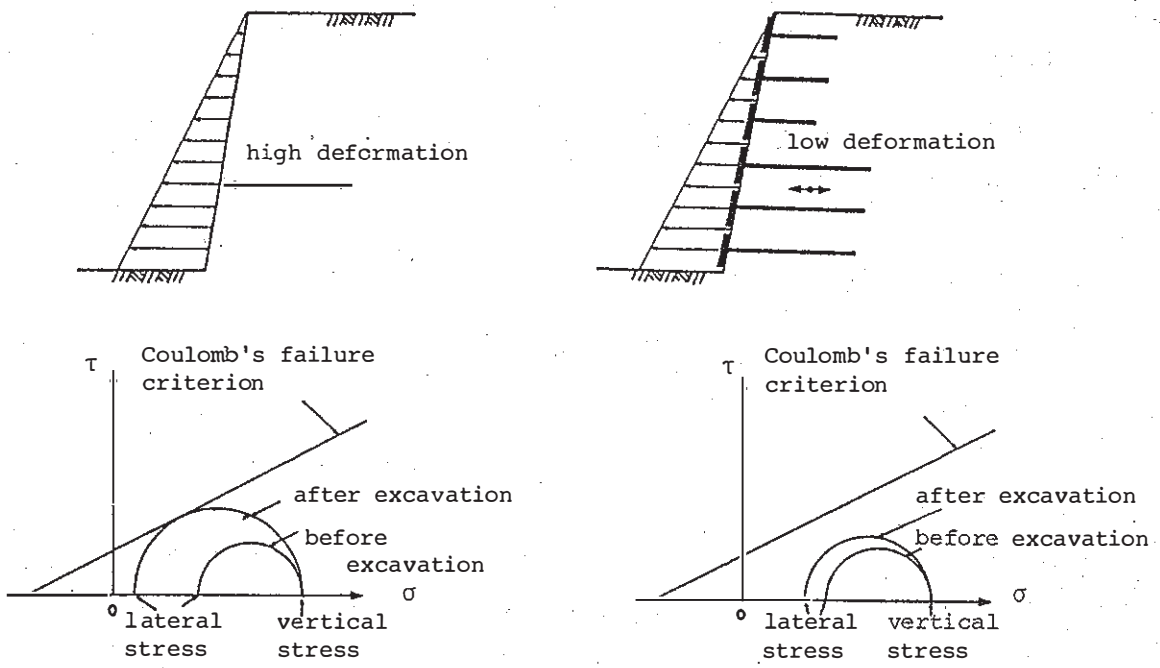
Where

- F_s : safety factor of the slip line
- C : ground cohesion
- ϕ : internal friction angle of the ground
- σ : normal stress on the surface of the slip line
- τ : shear stress on the surface of the slip line

and integration is executed along the slip line.

There are numerous slip lines to be considered. The line which has the minimum safety factor is determined by using the optimization technique. Here, Dynamic Programming (1973) is used. Dynamic Programming resolves multistage optimization problems.

In order to apply Dynamic Programming to this problem the appropriate number of stages in a given slope is established as shown schematically in Fig.3. At each stage the appropriate number of states is provided, which is indicated by the points in Fig.3.



a) unreinforced slope

b) reinforced slope

Fig.1 Principle of earth reinforcement

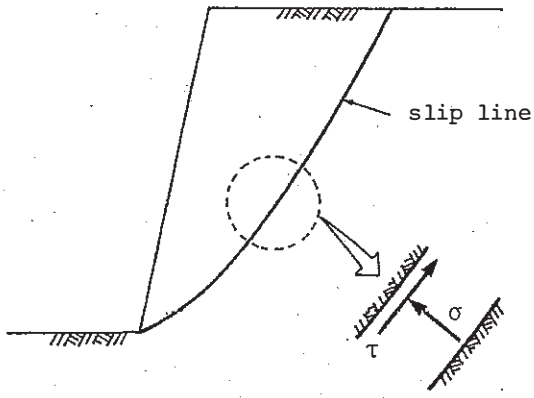


Fig.2 Definition of the safety factor

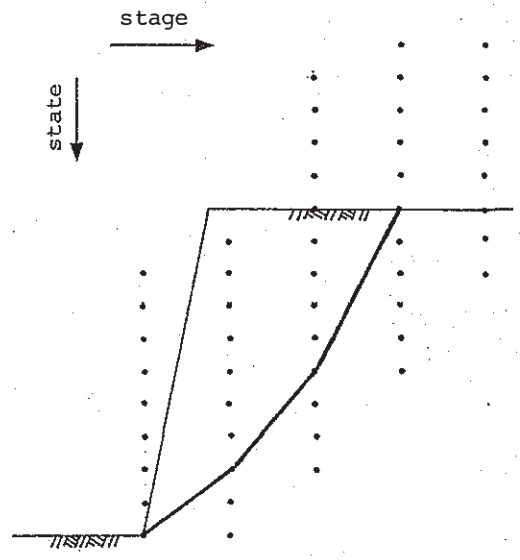


Fig.3 Representation of stages and states

Now, we consider a slip line made by connecting points at two arbitrary successive stages as shown in Fig.3.

For this slip line, Eq.(1) is rewritten as

$$F_s = \frac{\Sigma R_i}{\Sigma T_i} \quad (i=2,M) \qquad (2)$$

Where

$$R_i = \int_{s(j,k)} (c+\sigma\cdot\tan\phi)\cdot d_s \qquad (3)$$

$$T_i = \int_{s(j,k)} \tau\cdot d_s \qquad (4)$$

Here, S(j,k) denotes the line connecting point j at the stage i-1 and point k at the stage i(Fig.4). M is the total number of stages.

In the execution of equations (3) and (4) the stress factors σ and τ obtained from FEM analysis are used. Here, it is assumed that stress is constant in each FEM element.

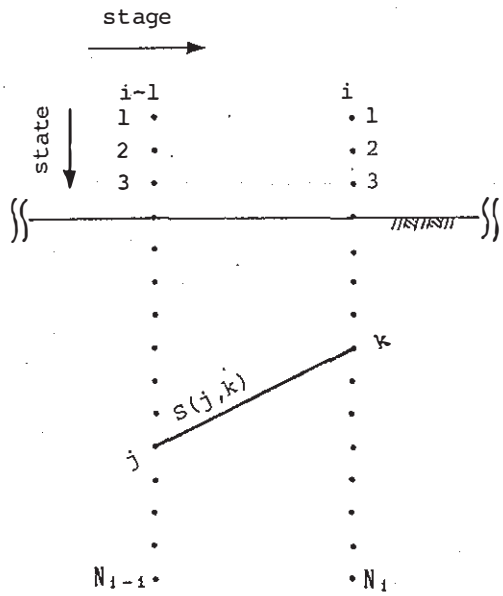


Fig.4 Application of dynamic programming

Further, we define the new auxiliary function G as

$$G = \sum (R_i - F_s \cdot T_i) \qquad (i=2, M) \qquad (5)$$

It is known that minimizing the function F_s in Eq.(2) is equivalent to minimizing the new function G.

According to the "principle of optimality", which is the central concept in dynamic programming, the minimum value of G between the initial stage and point k, the function $H_i(k)$, is given by the sum of the minimum value of G between the initial stage and any state j at the previous stage i-1 and the change in G on passing between the two states j and k. This is expressed as

$$H_i(k) = \min_{1 \leqq j \leqq N_{i-1}} [H_{i-1}(j) + D_i(j,k)] \qquad (6)$$
$$(i=2, M) \quad (k=1, N_i)$$

where, N_i is the number of states at stage i. $D_i(j,k)$ is the change in G on passing from the point j to the point k and is expressed as

$$D_i(j,k) = R_i - F_s \cdot T_i \qquad (7)$$

After the calculation of Eq.(6) is the final stage, the minimum value of G is obtained in the following equation.

$$G_{min} = \min_{1 \leqq k \leqq N_M} H_M(k) \qquad (8)$$

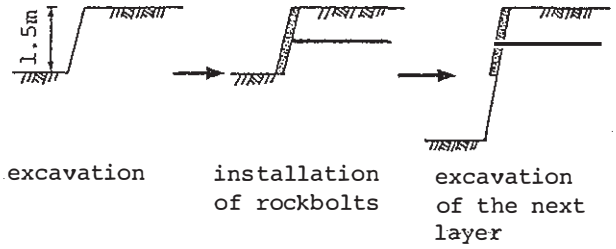


Fig.5 Excavation procedure

Table 1. The material properties adopted for the analysis

Materials	Items	Values	
Ground	Young's modulus	850	(tf/m^2)
	Poison's ratio	0.33	
	Coefficient of lateral pressure	0.5	
	Unit weight	1.8	(tf/m^3)
	Cohesion	1.8	(tf/m^2)
	Internal friction angle	30°	
Bolt	Young's modulus	2.1×10^7	(tf/m^2)
	Diameter	2.5	(cm)
Plate	Young's modulus	2.0×10^6	(tf/m^2)
	Thickness	10.0	(cm)

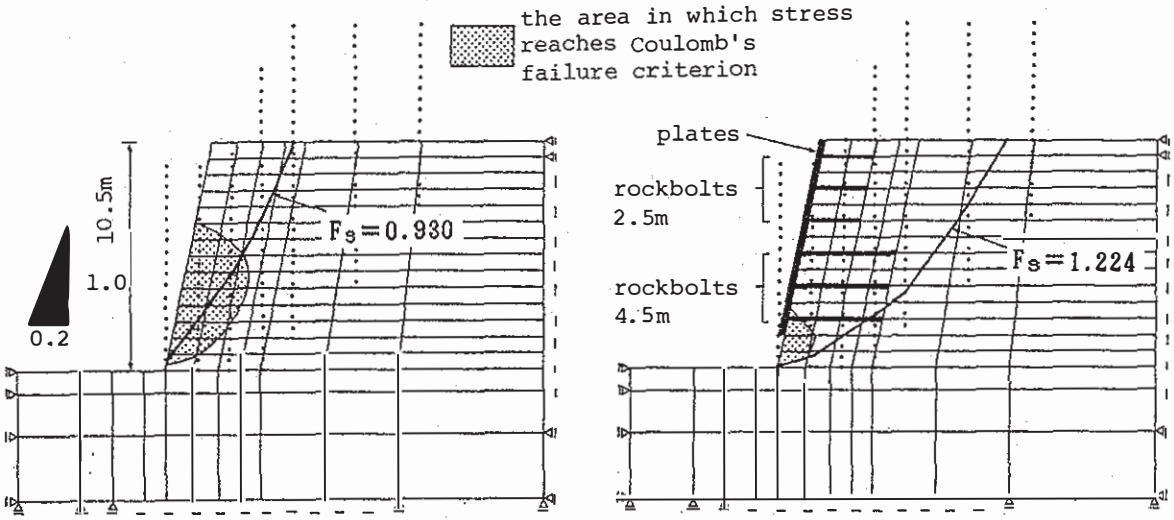
The critical slip line is obtained by tracing back the path which gives G_{min}.

3 NUMERICAL RESULTS

The procedure described herein was applied in the stability analysis of two cut slopes. One slope was unreinforced. The other was reinforced by short rockbolts and large-sized bearing plates placed at 1.5m intervals on the excavation as shown in Fig.5.

The ground stress was analyzed by elastic FEM analysis. Rockbolts were treated as beam elements and plates were treated as plane strain elements. The material properties adopted here are shown in Table 1.

The area where stress exceeds Coulomb's failure criterion is shown in Fig.6. The danger area in the reinforced slope is smaller than that in the unreinforced slope.



a) unreinforced slope

b) reinforced slope

Fig.6 Results of FEM analysis and search for the slip line

The slip line having the minimum safety factor was searched for in each slope as shown in Fig.6. Compared with the slip line of the unreinforced slope, that of the reinforced slope was deeper and its safety factor was higher.

4 CONCLUSIONS

The procedure of searching for the slip line having the minimum safety factor in the stress field obtained from FEM was adopted for the stability analysis of slopes reinforced with rockbolts.

FEM analysis is used in this procedure. As a result, the interaction between the ground and the rockbolts can be examined.

In the analysis performed herein, it was assumed that there was perfect cohesion between the rockbolts and the ground surrounding them. But in practice this may not be the case. Therefore, the safety factor obtained herein may be somewhat greater than that which would actually be achieved.

In the future, the results of field measurements or experimental studies on the interaction between the ground and rockbolts should be introduced into the analysis performed herein.

For example, field measurements or experimental studies might indicate that less rigid rockbolts could be used.

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