

11. THE STABILITY OF SLOPES

11.1 INTRODUCTION

The quantitative determination of the stability of slopes is necessary in a number of engineering activities, such as:

- (a) the design of earth dams and embankments,
- (b) the analysis of stability of natural slopes,
- (c) analysis of the stability of excavated slopes,
- (d) analysis of deepseated failure of foundations and retaining walls.

Quite a number of techniques are available for these analyses and in this chapter the more widely used techniques are discussed. Extensive reviews of stability analyses have been provided by Chowdhury (1978) and by Schuster and Krizek (1978). In order to provide some basic understanding of the nature of the calculations involved in slope stability analyses the case of stability of an infinitely long slope is initially introduced.

11.2 FACTORS OF SAFETY

The factor of safety is commonly thought of as the ratio of the maximum load or stress that a soil can sustain to the actual load or stress that is applied. Referring to Fig. 11.1 the factor of safety F , with respect to strength, may be expressed as follows:

$$F = \frac{\tau_{ff}}{\tau} \quad (11.1)$$

where τ_{ff} is the maximum shear stress that the soil can sustain at the value of normal stress of σ_n , τ is the actual shear stress applied to the soil.

Equation 11.1 may be expressed in a slightly different form as follows:

$$\tau = \frac{c}{F} + \frac{\sigma_n \tan \phi}{F} \quad (11.2)$$

Two other factors of safety which are occasionally used are the factor of safety with respect to cohesion, F_c , and the factor of safety with respect to friction, F_ϕ . The factor of safety with respect to cohesion may be defined as the ratio between the actual cohesion and the cohesion required for stability when the frictional component of strength is fully mobilised.

This may be expressed as follows:

$$\tau = \frac{c}{F_c} + \sigma_n \tan \phi \quad (11.3)$$

The factor of safety with respect to friction, F_ϕ , may be defined as the ratio of the tangent of the angle of shearing resistance of the soil to the tangent of the mobilised angle of shearing resistance of the soil when the cohesive component of strength is fully mobilised. One way in which this may be expressed is as follows:

$$\tau = c + \frac{\sigma_n \tan \phi}{F_\phi} \quad (11.4)$$

A further factor of safety which is sometimes used is F_H , the factor of safety with respect to height. This is defined as the ratio between the maximum height of a slope to the actual height of a slope and may be expressed as follows:

$$F_H = \frac{H_{\max}}{H} \quad (11.5)$$

The factors of safety F_c , F_ϕ , F_H are only occasionally used in slope stability analyses. The factor of safety with respect to strength (F) as expressed in equation (11.2), is the one which is almost universally used in calculations.

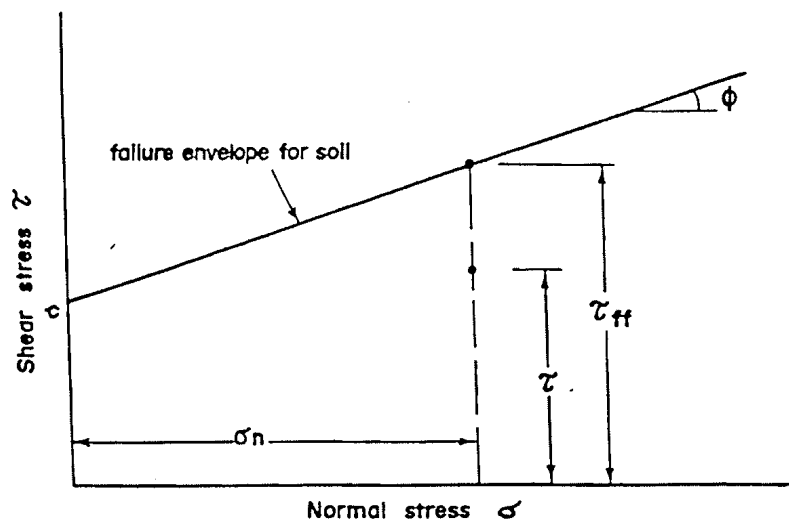


Fig. 11.1 Definition Diagram for Factor of Safety

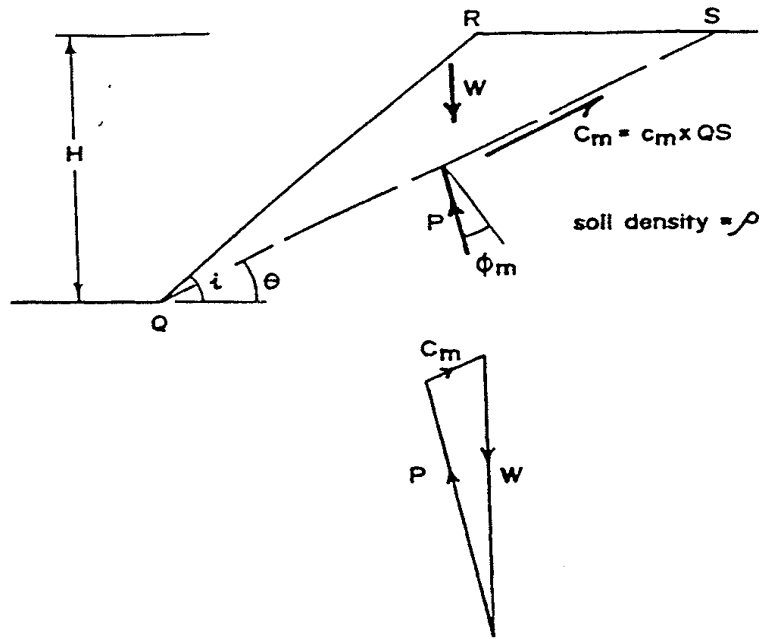


Fig. 11.2 Culmann Approach to Slope Stability

11.3 CULMANN METHOD

A technique for the calculation of slope stability based upon the assumption of a plane surface of failure through the toe of the slope has been proposed by Culmann (see Taylor, 1948). In Fig. 11.2 the line QS represents a plane potential failure surface. The forces acting on the wedge QRS are indicated on the figure as the weight of the wedge W , the mobilised cohesive force C_m and the mobilised frictional force P . ϕ_m is the mobilised angle of shearing resistance. These three forces are placed in equilibrium to yield the following expression:

$$\frac{c_m}{\rho g H} = \frac{\cos(i + \phi_m - 2\theta) - \cos(i - \phi_m)}{4 \cos \phi_m \sin i} \quad (11.6)$$

where the symbols are indicated in Fig. 11.2. The term on the left hand side of this equation is known as the stability number. Since QS is an arbitrarily selected trial plane inclined at an angle θ to the horizontal, it is necessary to find the most dangerous plane along which sliding is most likely. This is done by setting the first derivative with respect to θ of the expression above equal to zero. This results in determination of the critical inclination θ_{crit} given by the following expression:

$$\theta_{crit} = \frac{1}{2}(i + \phi_m)$$

Substitution of θ_{crit} into equation (11.6) yields the maximum value of the stability number,

$$\frac{c_m}{\rho g H} = \frac{1 - \cos(i - \phi_m)}{4 \cos \phi_m \sin i} \quad (11.7)$$

The factor of safety with respect to strength may be determined from equation (11.7) by a trial and error process similar to that described in section 11.7.

This method of slope stability analysis is not widely used since it has been found that plane surfaces of sliding are observed only with very steep slopes, and for relatively flat slopes the surfaces of sliding are almost always curved.

EXAMPLE

Referring to Fig. 4.2

$$\begin{aligned} H &= 16\text{m} \\ \tan i &= 2/3 \\ \tan \theta &= 1/3 \\ c &= 10\text{kPa} \\ \phi &= 35^\circ \end{aligned}$$

and the weight of the soil wedge QRS is 3.5MN/m. Calculate the factor of safety (F) against sliding along the potential failure surface QS.

For this problem, equation (11.7) is not applicable since the angle (θ) has been specified and this may not necessarily be equal to the critical value (θ_{crit}). Equation (11.6) can be used and substitution into this equation of the given information yields the following expression

$$\frac{c_m}{291.67} = \frac{\cos(\phi_m - 3.18^\circ) - \cos(33.69^\circ - \phi_m)}{2.219 \cos \phi_m} \quad (11.8)$$

If equation (11.2) is rewritten as

$$\tau = c_m + \sigma_n \tan \phi_m$$

it is seen that the factor of safety (F) may be expressed as

$$F = c/c_m = \tan \phi / \tan \phi_m \quad (11.9)$$

By using equations (11.7) and (11.9) and using successive approximation the values of ϕ_m and c_m may be determined.

$$\phi_m = 15.30^\circ \text{ and } c_m = 3.91 \text{ kPa}$$

which leads to a factor of safety (F) of 2.56.

An alternative and possibly simpler technique that may be used for this problem is to express the factor of safety (F) in terms of forces instead of stresses.

$$\begin{aligned}
 F &= \frac{\text{maximum forces tending to resist sliding down the plane QS}}{\text{forces tending to cause sliding down the plane QS}} \\
 &= \frac{C + N \tan \phi}{T} \qquad (11.10)
 \end{aligned}$$

where C = cohesive force acting on plane QS

$$= c \times \text{length QS} \times 1$$

N = resolved part of W acting normal to plane QS

$$= W \cos \theta$$

T = resolved part of W acting down the plane QS

$$= W \sin \theta$$

$$\therefore F = \frac{10 \times 50.6 \times 1 + 3500 \times 0.949 \times 0.700}{3500 \times 0.316}$$

$$= 2.56$$

11.4 THE $\phi = 0$ METHOD OF SLOPE STABILITY ANALYSIS

Since the surfaces of sliding for many slope failures have been observed to follow approximately the arc of a circle, most of the commonly used analytical techniques for calculation of slope stability involve the assumption of a circular failure arc. Most of the techniques discussed in this chapter are based upon this assumption. For composite failure surfaces, analyses have been developed by Morgenstern and Price (1965) and by Janbu (1973).

The problem is illustrated in the upper part of Fig. 11.3. The forces acting on the sliding wedge of soil are the weight W, normal stresses which act around the failure surface and resisting shear stresses τ which also act around the failure surface. The factor of safety F may be defined for this situation as follows:

$$\begin{aligned}
 F &= \frac{\text{sum of moments of maximum resisting forces}}{\text{sum of moments of moving forces}} \\
 &= \frac{\tau_{\max} \times \text{arc length} \times R}{Wd} \quad (11.11)
 \end{aligned}$$

In this equation the moments have been taken about the centre of the circle, part of which forms the failure surface so that the normal stresses do not enter into the calculation.

It will be noted that in equation (11.11) the maximum shear stress (τ_{\max}) has been assumed to be a constant. If this shear stress varies with the position along the sliding surface, it would be necessary to integrate the shear stress around the arc for use in equation (11.11).

In the special case where the slope is formed of a saturated clay the angle of shearing resistance (ϕ_u) will be zero for the short term case. The maximum resisting shear stress around the failure arc will then be equal to the undrained cohesion (c_u). If the undrained cohesion is a constant around the failure surface then equation (11.11) may be rewritten as follows:

$$F = \frac{c_u R \times \text{arc length}}{Wd} \quad (4.12)$$

This total stress analysis is commonly referred to as the $\phi_u = 0$ method. This method has been widely and successfully used in practice for the evaluation of the short term stability of saturated clay slopes. For example, Ireland (1954) has demonstrated the validity of this technique in the analysis of the short term stability of a slope excavated in saturated soil.

For the case where the angle of shearing resistance is not equal to zero the situation is not as straightforward as described above because of the necessity to determine the frictional component of the resisting shear stresses. For this case the forces acting on the block are shown in the lower part of Fig. 11.3. These forces (derived from effective stresses) are:

- (a) the mobilised cohesion force (C'_m), for which the line of action is known and the magnitude of which can be expressed in terms of the effective cohesion (c') and the factor of safety (F),
- (b) the effective normal force (N'), the magnitude and line of action of which are unknown since it depends upon the distribution of the normal effective stress around the circular arc,

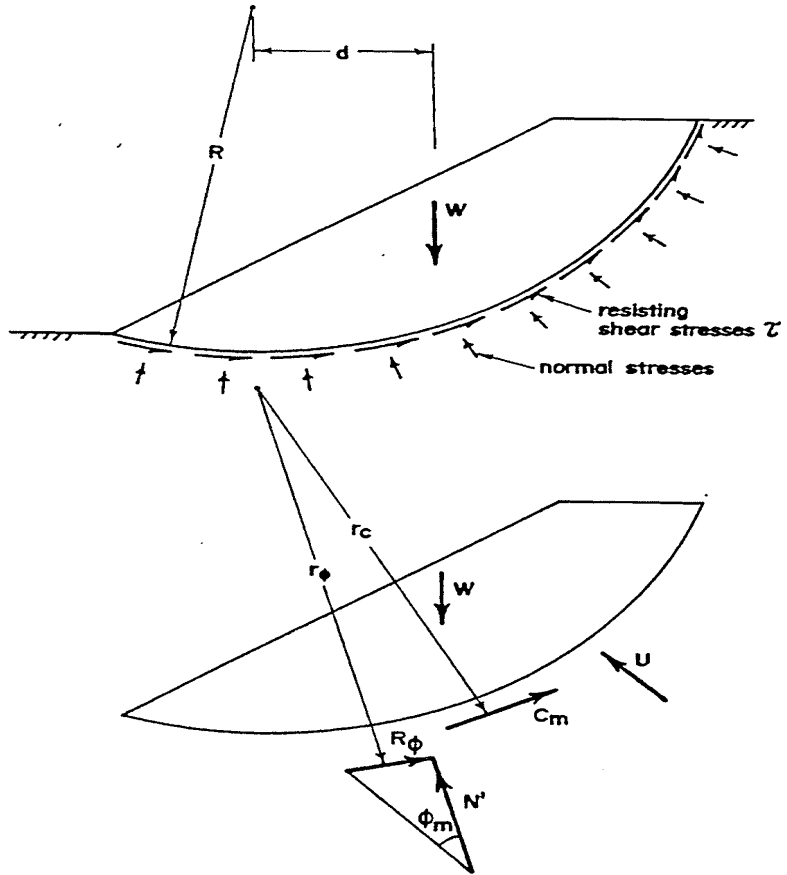


Fig. 11.3 Forces Involved in Calculations for Stability of Slopes

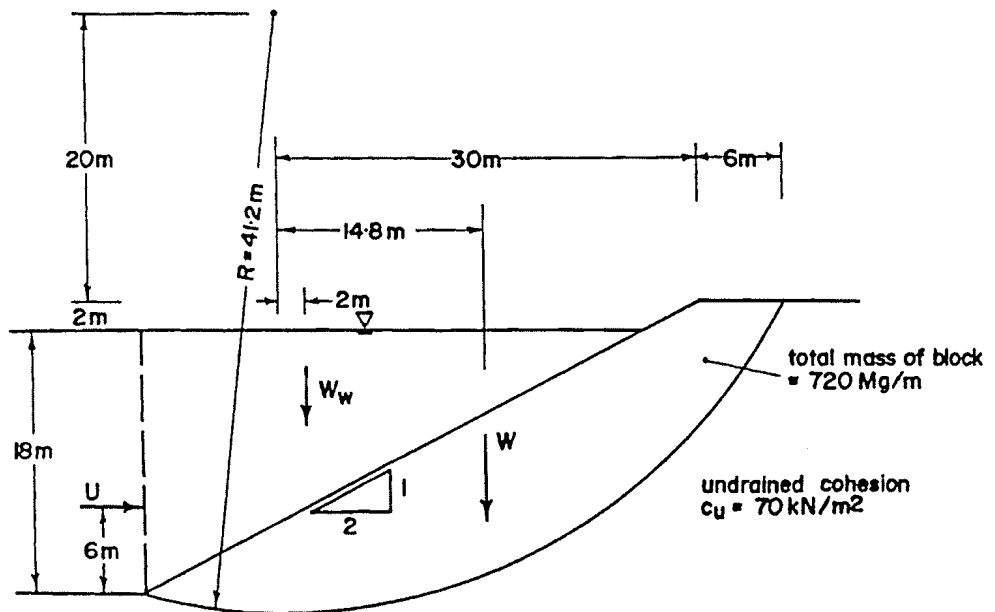


Fig. 11.4

- (c) R_ϕ which is the frictional force acting around the arc. This force is normal to the force N' , has a magnitude equal to $N' \tan \phi'/F$ where ϕ' is the effective angle of shearing resistance, but the line of action of this force R_ϕ is unknown. U , the pore pressure force, is known from seepage or other considerations.

This means that there are four unknowns altogether, the factor of safety F , the magnitude of N' , the direction of N' , and r_ϕ to locate the line of action of the frictional force R_ϕ . Since there are only three equations of static equilibrium, this problem is indeterminate to the first degree. In order to solve the problem some assumption has to be made to remove one of the unknowns. One commonly made assumption involves the distribution of the normal effective stress around the failure arc. This will enable the direction of the effective normal force N' to be evaluated.

EXAMPLE

Evaluate the short term stability for the dam shown in Fig. 11.4. The embankment consists of a saturated soil for which the angle of shearing resistance $\phi_u = 0$ and the undrained cohesion $c_u = 70\text{kN/m}^2$. The calculation is to be carried out for the reservoir depth of 18m and for the case where the reservoir has been completely emptied.

In the calculations, the forces W_w and U will have moments about the centre of the circle and therefore must be evaluated.

Evaluating the forces (per m) acting on the block:

$$W = 720 \times 9.81 = 7060\text{kN} = 7.06\text{MN}$$

$$W_w = \frac{1}{2} \times 36 \times 18 \times 1.0 \times 9.81 = 3180\text{kN} = 3.18\text{MN}$$

$$U = \frac{1}{2} \times 18 \times 1.0 \times 9.81 \times 18 = 1590\text{kN} = 1.59\text{MN}$$

$$\begin{aligned} \text{maximum cohesive force } C &= c_u \times \text{arc length} \\ &= 70 \times 41.2 \times 1.32 \\ &= 3.8\text{MN} \end{aligned}$$

When moments are taken about the centre of the circle, there will be no moments due to the normal stresses and pore pressures acting around the arc; so these stresses can be ignored.

$$\begin{aligned}
 \text{Factor of Safety } F &= \frac{\Sigma \text{ moments of maximum resisting forces}}{\Sigma \text{ moments of moving forces}} \\
 &= \frac{3.8 \times 41.2}{7.06 \times 14.8 + 3.18 \times 2 - 1.59 \times 34} \\
 &= \frac{156.6}{104.5 + 6.4 - 54.0} \\
 &= 2.75
 \end{aligned}$$

On occasions the force U is considered as a resisting force, in which case,

$$\begin{aligned}
 F &= \frac{156.6 + 54.0}{104.5 + 6.4} \\
 &= 1.90
 \end{aligned}$$

This illustrates that a different answer can be obtained depending upon the precise definition of the factor of safety. The former calculation yielding a value of F of 2.75 is the more usual one that is performed.

When the water is removed,

$$\begin{aligned}
 F &= \frac{156.6}{104.5} \\
 &= 1.50
 \end{aligned}$$

so the slope will still be stable.

11.5 ORDINARY METHOD OF SLICES

In cases where the effective angle of shearing resistance is not constant over the failure surface, such as in zoned earth dams where the failure surface might pass through several different materials, the friction circle method cannot be used. A 'slices' method, is more appropriate in this situation. With a method of slices the sliding wedge PQS as shown in Fig. 11.5 is subdivided

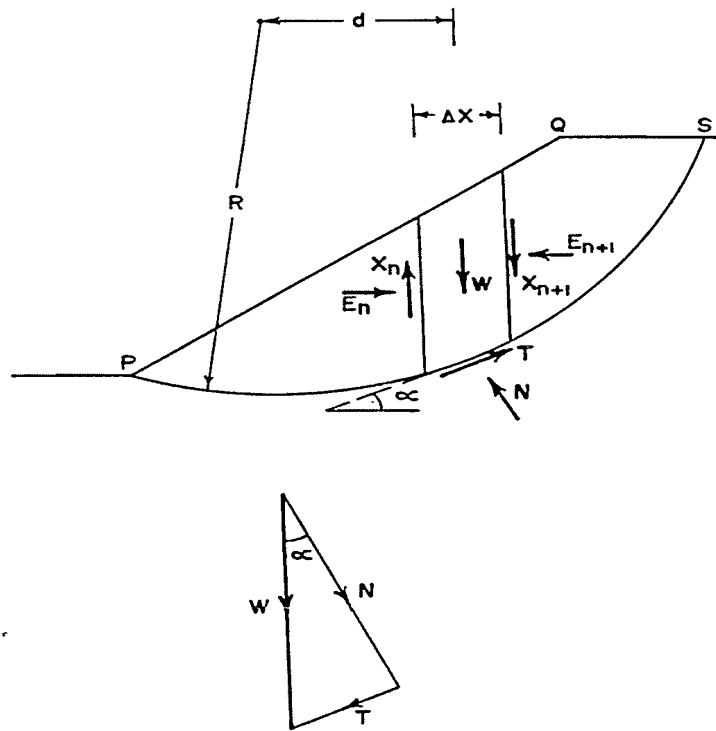


Fig. 11.5 Illustration of Ordinary Method of Slices

vertically into slices. The factor of safety is determined by examining the contributions to the moving and resisting forces provided by each slice.

The forces acting on a typical slice are shown in Fig. 11.5. These forces are the weight of the slice W , the normal and tangential forces acting on the lower boundary of the slice and the side forces indicated by X and E which act on the sides of the slice. With the Ordinary Method of Slices sometimes known as the Fellenius Method or the Swedish Circle Method (Fellenius (1936), and May and Brahtz (1936)), a number of simplifying assumptions are made in order to render the problem determinate.

Firstly it is assumed that the side forces X and E may be neglected and secondly, that the normal force N , may be determined simply by resolving the weight W of the slice in a direction normal to the arc, at the mid point of the slice, as shown in the lower part of Fig. 11.5.

$$N = W \cos \alpha$$

where α is the angle of inclination of the potential failure arc to the horizontal at the mid point of the slice

$$\begin{aligned}
\text{Effective normal force } N' &= N - U \\
&= W \cos \alpha - u \Delta X \sec \alpha \\
\text{total maximum resisting force } T_{\max} &= \Sigma(c' + \sigma' \tan \phi') \Delta X \sec \alpha \\
&= \Sigma (c' \Delta X \sec \alpha + N' \tan \phi') \\
&= \Sigma (c' \Delta X \sec \alpha + \tan \phi' (W \cos \alpha - u \Delta X \sec \alpha)) \\
\text{Factor of Safety} &= \frac{\text{sum of moments of maximum resisting forces}}{\text{sum of moments of moving forces}} \\
&= \frac{\Sigma T_{\max} R}{\Sigma W d} \\
&= \frac{\Sigma T_{\max} R}{\Sigma W R \sin \alpha} \\
&= \frac{\Sigma T_{\max}}{\Sigma W \sin \alpha} \\
&= \frac{\Sigma \text{ maximum resisting forces around the arc}}{\Sigma \text{ moving forces around the arc}} \\
F &= \frac{\Sigma (c' \Delta X \sec \alpha + \tan \phi' (W \cos \alpha - u \Delta X \sec \alpha))}{\Sigma W \sin \alpha}
\end{aligned}$$

(11.13)

This procedure would then be followed for a number of trial failure surfaces until the lowest factor of safety is found.

Some difficulties may be experienced with equation (11.13). Negative values of the effective normal force N' may be encountered for large values of the angle α when pore pressures are present. This method is widely used by dam constructing authorities even though it has been demonstrated by Whitman and Moore (1963) and this method of analysis is unsound and yields factors of safety which are smaller than the correct values.

EXAMPLE

Using the Ordinary Method of Slices, determine the factor of safety for the slope undergoing seepage and for the failure surface shown in Fig. 11.6. The soil properties are as follows:

total density	=	2Mg/m^3
effective cohesion c'	=	30kN/m^2
effective friction angle ϕ'	=	30°

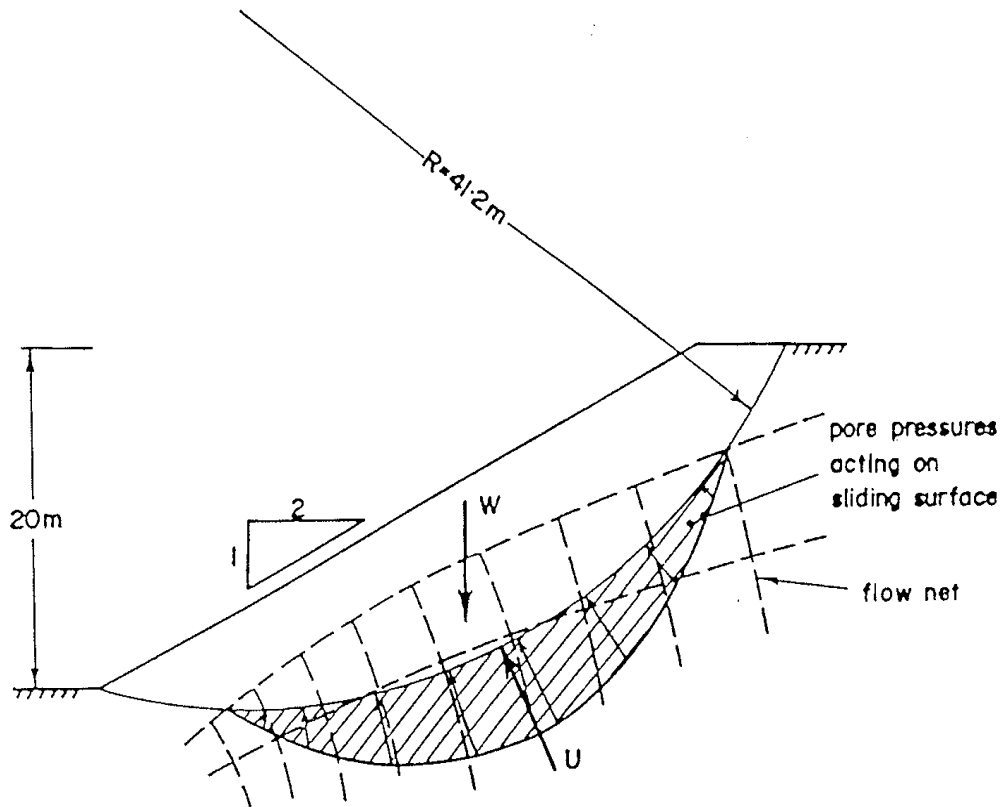


Fig. 11.6

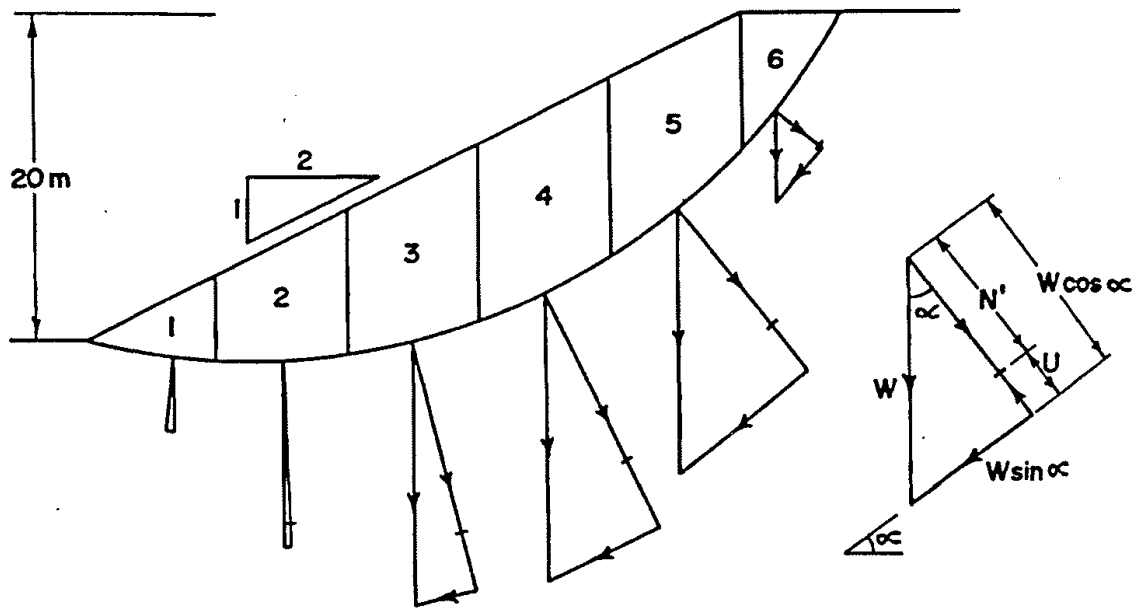


Fig. 11.7 Stresses and Forces Acting on a Typical Slice

The sliding wedge has been subdivided into six slices as shown in Fig. 11.7. The weights of the slices have been determined and the average pore pressures acting on the bases of the slices have been determined from the flownet which is drawn in Fig. 11.6. The effective normal force N' may be determined either graphically as shown in Fig. 11.5 or mathematically as shown in Table 11.1. The remaining calculations for this problem are set out in Table 11.1.

11.6 BISHOP METHOD OF SLICES

A slices method of slope stability analysis which involves a different procedure and gives different answers compared with the Ordinary Method of Slices has been proposed by Bishop (1955). With this method, the analysis is carried out in terms of stresses instead of forces which were used with the Ordinary Method of Slices. The stresses and forces which act on a typical slice and which are taken into account in the analysis are shown in Fig. 11.8. The major difference between the Bishop Method and the Ordinary Method of Slices is that resolution of forces takes place

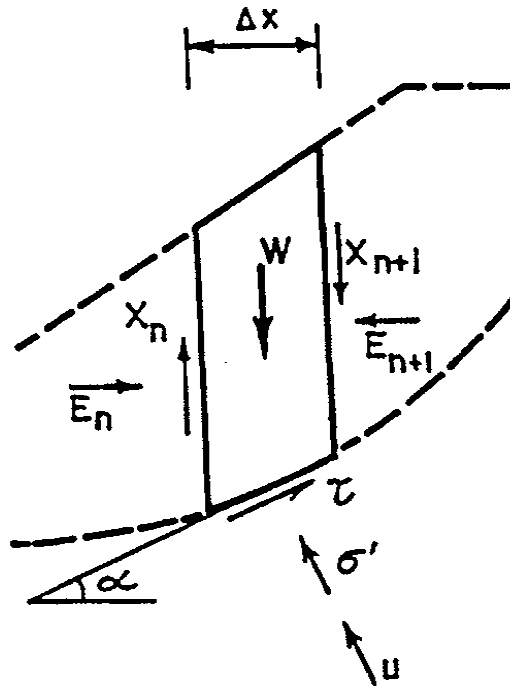


Fig. 11.8 Stresses and Forces Acting on a Typical Slice

TABLE 11.1

CALCULATIONS FOR ORDINARY METHOD OF SLICES

Slice	Slice Width (Δx) m	$\sin \alpha$	Weight of Slice (W) kN	Pore Pressure Force (U) kN	$W \sin \alpha$ kN	$W \cos \alpha$ (N) kN	N - U (N') kN	$N' \tan \phi'$ kN	$c' \Delta X \sec \alpha$ kN
1	8	-.111	450	0	- 50	447	447	258	243
2	8	.049	1118	150	54	1117	967	558	243
3	8	.242	1590	370	384	1542	1172	676	246
4	8	.436	1742	450	760	1568	1118	645	270
5	8	.630	1590	340	1000	1235	895	516	318
6	6	.775	570	20	442	360	340	196	315
Totals					2590			2849	1635

$$\begin{aligned}
 F &= \frac{\Sigma (c' \Delta X \sec \alpha + N' \tan \phi')}{S W \sin \alpha} \\
 &= \frac{1635 + 2849}{2590} \\
 &= 1.73
 \end{aligned}$$

in the vertical direction instead of a direction normal to the arc (a direction which is different for each slice). This means that with the Bishop Method the side forces E acting on the sides of the slices will not enter into the analysis. In the simplified Bishop Method which is described here, it is assumed that the shear side forces X may be neglected without introducing serious error into the analysis. A more rigorous method in which the side forces X are taken into account is found to yield answers only slightly different from that obtained from the simplified Bishop Method. The simplified analysis is as follows:

$$\tau = \frac{1}{F} (c' + \sigma' \tan \phi')$$

To find σ' resolve forces in the vertical direction to obtain

$$W - \frac{1}{F} (c' + \sigma' \tan \phi') \Delta X \tan \alpha - (\sigma' + u) \Delta X = 0$$

$$\therefore \sigma' = \frac{W - u \Delta X - \frac{1}{F} c' \Delta X \tan \alpha}{\Delta X (1 + (\tan \phi' \tan \alpha)/F)}$$

$$\text{Now } F = \frac{\Sigma \text{ maximum resisting forces around arc}}{\Sigma \text{ moving forces around arc}}$$

$$= \frac{\Sigma (c' + \sigma' \tan \phi') \Delta X \sec \alpha}{\Sigma W \sin \alpha}$$

$$= \frac{\Sigma \left\{ \left[c' \Delta X + (W - u \Delta X) \tan \phi' \right] \frac{1}{M_\alpha} \right\}}{\Sigma W \sin \alpha} \quad (11.14)$$

$$\text{where } M_{\alpha} = \cos \alpha + \frac{\sin \alpha \tan \phi'}{F} \quad (4.15)$$

The factor of safety F appears on both sides of equation (11.14). Fortunately the solution converges rapidly, only two or three trials for F being necessary in solving the equation. A plot of M_{α} as given by equation (11.15) is presented in Fig. 11.9 to assist in the solution of equation (11.14).

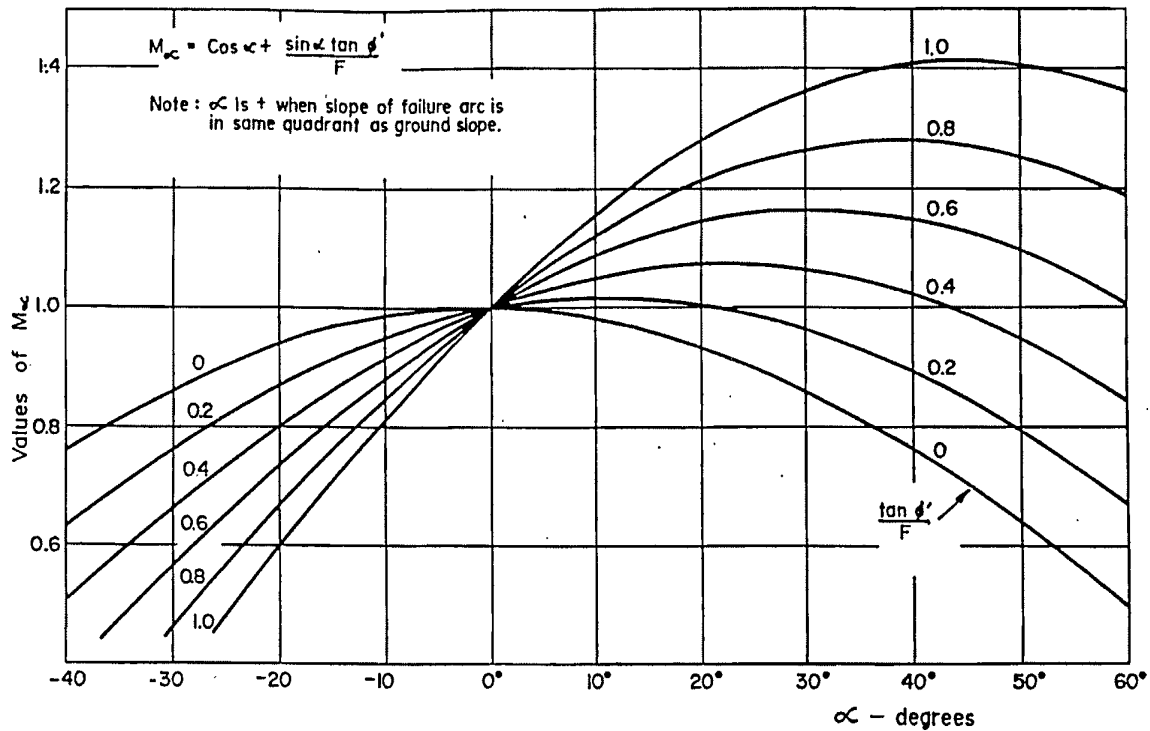


Fig. 11.9 Graph for Evaluating M_{α}

To facilitate the analyses of slope stability for a large number of potential failure surfaces and for a variety of conditions, use is made of computer programs.

The Bishop Method yields factors of safety which are higher than those obtained with the Ordinary Method of Slices. Further, the two methods do not lead to the same critical circle. It has also been found that the disagreement increases as the central angle of the critical circle increases. Analyses by more refined methods involving consideration of the forces acting on the sides of slices show that the simplified Bishop Method yields answers for factors of safety which are very close to the correct answer.

EXAMPLE

Using the simplified Bishop Method, determine the factor of safety for the problem illustrated in Figs. 11.6 and 11.7. This is the same problem that has been solved in this chapter by means of friction circle method and by means of the Ordinary Method of Slices.

The sliding wedge has been subdivided into the same six slices that were used for the solution by means of the Ordinary Method of Slices. The evaluation of the factor of safety by means of the Bishop Method is carried out in tabular form as shown in Table 11.2.

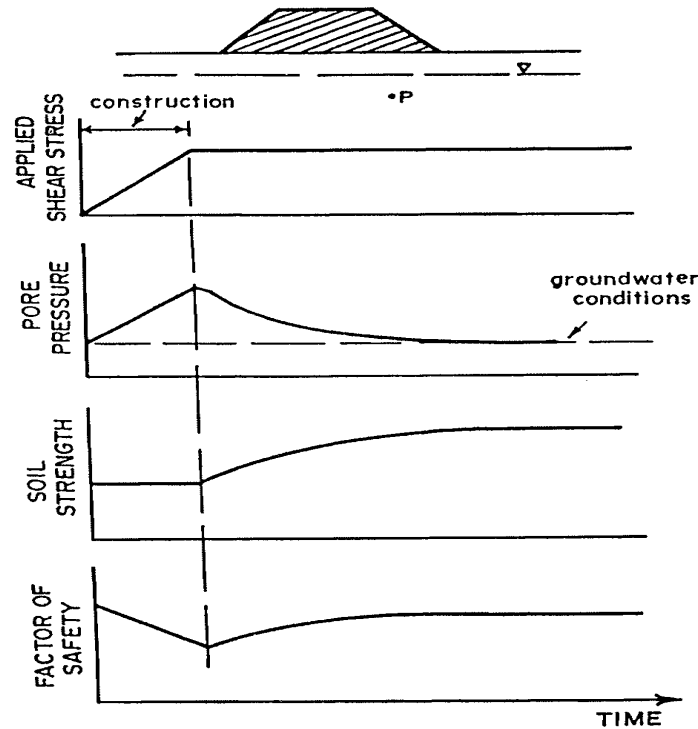
TABLE 11.2
CALCULATIONS FOR BISHOP METHOD OF SLICES

Slice	1	2	3	4	5	6			
	Slice Width (ΔX) m	Weight of Slice (W) kN	Pore Pressure u kN/m ²	W sin α kN	c ΔX + (W - u ΔX) tan ϕ' kN	M_α		$\frac{\text{col. (5)}}{\text{col. (6)}} - \text{kN}$	
						trial (1) F = 2.0	trial (2) F = 1.85	trial (1) F = 2.0	trial (2) F = 1.85
1	8	450	0	-50	500	.96	.96	520	520
2	8	1118	18.7	54	799	1.01	1.01	790	790
3	8	1590	45.1	384	950	1.03	1.03	920	920
4	8	1742	50.0	760	1015	1.02	1.03	995	985
5	8	1590	32.4	1000	1010	.97	.98	1042	1030
6	6	570	2.0	442	502	.86	.87	585	576
Totals				2590				4852	4821

$$F_{(1)} = \frac{4852}{2590} = 1.88$$

$$F_{(2)} = \frac{4821}{2590} = 1.86$$

∴ Factor of Safety = 1.86



**Fig. 11.10 Variation of Safety Factor with Time for Soil Beneath a Fill
(After Bishop and Bjerrum, 1960)**

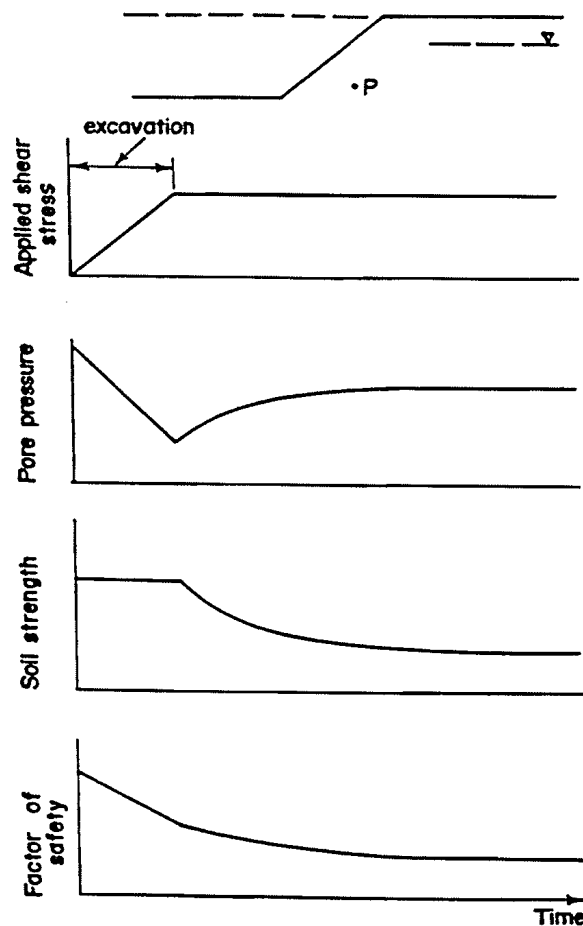
11.7 SHORT TERM AND LONG TERM STABILITY

In carrying out slope stability analyses for design purposes it is wise to check both short term and long term conditions. For the short term conditions an effective stress analysis could be used, but this will require an estimate of the pore pressures that will be developed. Alternatively a total stress analysis could be used, but this would only be applicable in cases where the pore pressure changes are entirely dependent upon stress changes. For long term conditions an effective stress analysis is normally carried out, since the pore pressures are usually independent of stress changes. For this analysis estimates of the pore pressures, for example, by means of flownets, are required.

In examining the stability of a foundation soil following embankment construction, the short term case is often more critical than the long term case. As discussed by Bishop and Bjerrum (1960), this is illustrated in Fig. 11.10 with an examination of the stress changes at a typical point P beneath the embankment.

In this case the pore pressure at point P at the end of construction is determined largely by the stress changes produced by the embankment. The pore pressure for the long term case, on the other hand, is determined by the ground water conditions. In this idealized example the factor of safety is considered as the ratio between the soil strength and the applied shear stress. It is seen that in this case the minimum factor of safety is obtained at the end of construction, that is, for short term conditions. As time elapses and the construction pore pressure dissipate the factor of safety increases as illustrated in the sketch.

On the other hand Fig. 11.11 illustrates the stress changes at a typical point P beneath an excavated slope. Here the pore pressures at the end of excavation are determined by the stress changes produced by the process of excavation. The long term pore pressures, as in the previous example are determined by the ground water conditions. In this case, it is seen that the soil strength decreases with time and the factor of safety also decreases with time, which makes the long term stability condition the critical one to be examined.



**Fig. 11.11 Variation of Safety Factor with Time for Excavation of a Slope
(after Bishop & Bjerrum, 1960)**

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