\[ F = \frac{c' + (\gamma z - \gamma_w h) \cos^2 \beta \tan \phi'_c}{\gamma z \sin \beta \cos \beta} \]
\[ = \frac{12 + (20 \times 4 - 9.81 \times 4) \cos^2 14^\circ \times \tan 24^\circ}{20 \times 4 \times \sin 14^\circ \times \cos 14^\circ} = 1.55 \]

9.4 Slope failure mechanisms in cohesive soils

The most usual methods of providing an analysis of stability in slopes in cohesive soils are based on a consideration of limiting plastic equilibrium. Fundamentally, a condition of limiting plastic equilibrium exists from the moment that a shear slip movement commences and strain continues at constant stress. It is first necessary to define the geometry of the slip surface; the mass of soil about to move over this surface is then considered as a free body in equilibrium. The forces or moments acting on this free body are evaluated and those shear forces acting along the slip surface compared with the available shear resistance offered by the soil.

Several forms of slip surface may be considered for cohesive soils as shown in Fig. 9.6. The simplest of these, suggested by Cullmann in 1866, consists of an infinitely long plane passing through the toe of the slope. Although the analysis of the free body equilibrium is simple in this case, the method yields factors of safety which grossly overestimate the true stability conditions. On the other hand, while the choice of a more complex surface, such as a log-spiral or an irregular shape, may produce results near to the actual value, the analysis tends to be long and tedious. For most purposes, a cylindrical surface, i.e. circular in cross-section, will yield satisfactorily accurate results without involving analytical routines of any great complexity.

The stability of a cut or built slope depends very largely on changes in the pore pressure regime. During the construction of embankments pore pressures
Drained stability – effective stress analyses

The slip mass is divided into a convenient number of slices of width $b$ as in worked example 9.9. The average height of each slice is measured off a scale drawing of the cross-section in two components $h_1$ and $h_2$. The weight of each slice is therefore:

$$W = (\gamma_1 h_1 + \gamma_2 h_2) b$$

As an alternative method to that used in worked example 9.9 (i.e. drawing the triangles of forces): in this example the angle $\alpha$ has been evaluated for each slice:

$$\alpha = \arcsin(x/R)$$

From eqn [9.15]:

$$F = \frac{\sum c' L + \tan \phi' \sum [W (\cos \alpha - r_0 \sec \alpha)]}{\sum W \sin \alpha}$$

which, since there are two layers, becomes:

$$F = \frac{[c'_1 L_{FB} + c'_2 L_{AF}] + \left[ \tan \phi'_1 \sum W (\cos \alpha - r_0 \sec \alpha) + \tan \phi'_2 \sum W (\cos \alpha - r_a \sec \alpha) \right]}{\sum W \sin \alpha}$$
Fig. 9.21

\[ L_{AB} = \theta R = 91.47 \times \frac{\pi}{180} \times 18.58 = 29.7 \text{ m} \]

From eqn [6.16]

\[ F = \frac{c'L_{AB} + \tan \phi' \sum N'}{\sum T} \]

\[ = \frac{10 \times 29.7 + \tan 28^\circ \times 1052}{814} = 1.05 \]

A similar analysis carried out on a microcomputer gave \( F = 1.074 \). Another computer analysis using Bishop’s simplified method gave \( F = 1.22 \).

**Worked example 9.10** Determine the factor of safety in terms of effective stress of the slope shown in Fig. 9.22 in respect of the trial circle shown. Assume that the pore pressure ratio \( r_u = 0.3 \) and that the soil properties are as follows:
The procedure is commenced by assuming a trial value for the $F$ on the right-hand side and then, using an iterative process, to converge on the true value of $F$ for a given trial circle. This is the routine procedure commonly used in programs designed for use on computers. Many of the program packages now available offer also the inclusion of multi-layer conditions, surcharge loads, variable pore pressure distribution and even the provision of berms and drains. In most problems, it is acceptable to adopt a constant average value for $r_w$. The factors of safety computed by this method may be slight underestimates, but with errors not usually exceeding 3 per cent, except in occasional unusual cases with deep base failure circles and $F$ less than unity. More accurate lower factors of safety are claimed for methods which account for the variation in seepage forces on and in the slice (King, 1989). However, such refinements depend even more on good estimates of pore pressures. Morrison and Greenwood (1989) have further examined the assumptions made in this method.

**Worked example 9.9** Determine the factor of safety in terms of effective stress for the slope in Fig. 9.21 in respect of the trial circle shown. The soil properties are as follows:

$c' = 10 \text{kPa} \quad \phi' = 28^\circ \quad \gamma = 18 \text{kN/m}^3$

The pore pressure distribution along the trial circle is obtained by sketching equipotentials at each slice centre.

Figure 9.21 shows how a partially graphical solution may be obtained. The slip mass has been divided into slices of width 3 m and the section drawn to an appropriate scale. The average height of each slice ($h$) is scaled off the diagram and its weight calculated.

$W = \gamma hb = 18 \times h \times 3 = 54.0h \text{kN/m}$

The length of the chord at the base of each slice is scaled off and the pore pressure force calculated.

$ul = h_w \times 9.81 \times l$

A triangle of forces is drawn at the base of each slice to obtain values of $N$ and $T$.

The calculations are tabulated below:

<table>
<thead>
<tr>
<th>Slice no.</th>
<th>h (m)</th>
<th>W (kN/m)</th>
<th>$h_w$ (m)</th>
<th>l (m)</th>
<th>N</th>
<th>ul</th>
<th>N'</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.6</td>
<td>32</td>
<td>0.6</td>
<td>3.2</td>
<td>31</td>
<td>19</td>
<td>12</td>
<td>-8</td>
</tr>
<tr>
<td>2</td>
<td>2.4</td>
<td>130</td>
<td>1.7</td>
<td>3.1</td>
<td>128</td>
<td>52</td>
<td>76</td>
<td>-20</td>
</tr>
<tr>
<td>3</td>
<td>4.6</td>
<td>248</td>
<td>3.6</td>
<td>3.0</td>
<td>248</td>
<td>106</td>
<td>142</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>6.4</td>
<td>346</td>
<td>4.6</td>
<td>3.1</td>
<td>341</td>
<td>140</td>
<td>201</td>
<td>57</td>
</tr>
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<td>7.4</td>
<td>400</td>
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<td>212</td>
<td>130</td>
</tr>
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<td>448</td>
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<td>3.5</td>
<td>381</td>
<td>175</td>
<td>206</td>
<td>218</td>
</tr>
<tr>
<td>7</td>
<td>7.2</td>
<td>389</td>
<td>4.1</td>
<td>3.9</td>
<td>298</td>
<td>157</td>
<td>141</td>
<td>251</td>
</tr>
<tr>
<td>8*</td>
<td>3.7</td>
<td>246</td>
<td>1.3</td>
<td>6.9</td>
<td>150</td>
<td>88</td>
<td>62</td>
<td>186</td>
</tr>
</tbody>
</table>

$\Sigma 1052 \quad 814$

* Width = 3.7 m
value for $F$ which may be as much as 50 per cent on the low side. Errors may also arise when $r_u$ is high and the circle is deep-seated or has a relatively short radius. In such cases, Bishop’s method is preferable.

**Bishop’s simplified method**

In reasonably uniform conditions and when also $r_u$ is nearly constant, it may be assumed that the tangential interslice forces are equal and opposite, i.e. $X_1 = X_2$ but that $E_1 \neq E_2$ (Fig. 9.20).

For equilibrium along the base of the slice:

$$0 = W \sin \alpha - \frac{t_l}{F} l = W \sin \alpha - C' L + N' \tan \phi'$$

So that

$$F = \frac{\Sigma (c' l + N' \tan \phi')}{\Sigma W \sin \alpha}$$

For equilibrium in a vertical direction:

$$0 = W - N' \cos \alpha - ul \cos \alpha - \frac{t_l}{F} l \sin \alpha$$

$$= W - N' \cos \alpha - ul \cos \alpha - C' l \sin \alpha - \frac{N' \tan \phi'}{F} \sin \alpha$$

Then

$$N' = \frac{W - (c'/F) l \sin \alpha - ul \cos \alpha}{\cos \alpha + (\tan \phi'/F) \sin \alpha}$$

After substituting for $l = b \sec \alpha$ and $N'$ rearranging

![Fig. 9.20 Bishop's simplified slice](image-url)
\( E_1 \) and \( E_2 \) = normal interslice forces
\( X_1 \) and \( X_2 \) = tangential interslice forces

The effects of any surcharge on the surface must be included in the computation of the body weight and other forces.

At the point of limiting equilibrium, the total disturbing moment will be exactly balanced by the moment of the total mobilised shear force along \( AB \).

\[
\sum \tau_m lR = \sum \frac{\tau_i}{F} lR = \sum W \sin \alpha R
\]

giving

\[
F = \frac{\sum \tau_i l}{\sum W \sin \alpha}
\]

Now in terms of effective stress,

\[
\tau_i = c' + \sigma_n \tan \phi'
\]

and

\[
\tau_i l = c'l + N' \tan \phi'
\]

so that

\[
F = \frac{\sum c'l + \sum N' \tan \phi'}{\sum W \sin \alpha}
\]

or if the soil is homogeneous

\[
F = \frac{c' L_{AB} + \tan \phi' \sum N'}{\sum W \sin \alpha}
\]

where \( L_{AB} = \text{arc length } AB = \theta R \)

A lot depends on how the values of \( N' \) are obtained. A number of methods have been suggested, some relatively simple and some which are quite rigorous. The most accurate estimates may be expected from rigorous methods, but may only be possible if a computer routine can be employed. A compromise may be arrived at by combining a simpler method of analysis with an increased factor of safety.

**Fellenius' method**

In this method, it is assumed that the interslice forces are equal and opposite and cancel each other out, i.e. \( E_1 = E_2 \) and \( X_1 = X_2 \). It is now only necessary to resolve the forces acting on the base of the slice, so that:

\[
N' = W \cos \alpha - ul = \gamma hb \cos \alpha - ub \sec \alpha \quad (l = b \sec \alpha)
\]

or putting \( u = r_u \gamma h \)

\[
N' = \gamma h(\cos \alpha - r_u \sec \alpha)b
\]

or \( \sum N' = \gamma b \sum h(\cos \alpha - r_u \sec \alpha) \)

Then substituting in eqn [9.13]:

\[
F = \frac{c' L_{AB} + \gamma b \tan \phi' \sum h(\cos \alpha - r_u \sec \alpha)}{\sum W \sin \alpha}
\]

[9.17]

The number of slices taken should not be less than five, and obviously a larger number would yield a better estimate of \( F \). Even so, this method tends to give a
(b) When $D = 1.5$, $\beta = 35^\circ$ and $\phi_u = 0$, then from Fig. 9.18(b):

$N = 0.168$ and $n = 0.6$

Factor of safety, $F = \frac{40}{0.168 \times 18 \times 8} = 1.65$

Thus, the presence of the harder layer constrains the failure mode to a smaller critical circle and so the factor of safety is larger, and the break-out point ($nH$) of this circle will be $0.6 \times 8 = 4.8$ m.

9.10 Drained stability – effective stress analyses

Stability analyses should be carried out in terms of effective stresses in problems where changes in pore pressure take place, such as existing embankments and spoil tips; also to estimate the long-term stability of slopes and in the case of overconsolidated clays for both immediate and long term conditions. Because of the variations in the stresses along a trial slip surface, the slip mass is considered as a series of slices. A trial slip circle is selected having a centre O and a radius $R$ (Fig. 9.19), and the horizontal distance between the two ends A and B divided into slices of equal breadth $b$.

The forces acting on a slice of length 1 m will be as follows:

$W$ = the body weight of the slice = $\gamma hb$

$N'$ = the effective normal reacting force at the base of the slice

$T$ = the shearing force induced along the base

$= W \sin \alpha$

$R_1$ and $R_2$ = forces imposed on the sides from adjacent slices – which may be resolved into:

![Fig. 9.19 Method of slices](image)

(a) Division of slip mass (b) Forces on a slice
the critical circle may pass in front of the toe and the chart shown in Fig. 9.18(a) is used. When the critical circle will be restricted to passing through the toe, the heavy broken lines on the chart must be used. The value of \( n \), giving the breakout point of the critical circle in front of the toe, can be obtained from the light broken lines.

**Worked example 9.7** A cutting in a saturated clay has a depth of 10 m. At a depth of 6 m below the floor of the cutting there is a layer of hard rock. The clay has an undrained cohesion of 34 kPa and a bulk unit weight of 19 kN/m\(^3\). Calculate the maximum safe slope that will provide a factor of safety of 1.25 against short-term shear failure.

Refer to Fig. 9.18(a).

\[
H = 10 \text{ m and } DH = 16 \text{ m} \quad : \quad D = 1.5
\]

Required stability number, \( N = \frac{c_u}{1.25\gamma H} = \frac{34}{1.25 \times 19 \times 10} = 0.143 \)

The point on the chart located by \( D = 1.5 \) and \( N = 0.143 \) gives a slope angle of \( \beta = 13^\circ \). Also, from the chart, \( n = 0.2 \). Hence the circle will break out 2.0 m in front of the toe.

**Worked example 9.8** A cutting in a cohesive soil has a slope angle of 35\(^\circ\) and a vertical height of 8 m. Using Taylor's stability method, determine the factor of safety against shear failure for the following cases:

(a) \( c_u = 40 \text{ kPa} \quad \gamma = 18 \text{ kN/m}^3 \quad D \text{ is large} \)
(b) \( c_u = 40 \text{ kPa} \quad \gamma = 18 \text{ kN/m}^3 \quad D = 1.5 \)

(a) When \( D \) is large, with \( \beta < 53^\circ \) then \( N = 0.181 \)

\[
\text{Factor of safety, } F = \frac{40}{0.181 \times 18 \times 8} = 1.53
\]
Fig. 9.18 Stability numbers for total stress analyses
(a) In terms of depth factor $D$ (b) Toe circles in terms of slope angle $\beta$

Hence, \[ F = \frac{c_u}{N\gamma H} \] \[ \text{[9.15]} \]

or since $c_{\text{mob.}} = c_u/F$, required $c_{\text{mob.}} = N\gamma H$

Values of $N$ related to the slope angle $\beta$, the angle of shearing resistance $\phi_u$ and the depth factor $D$ are given in the charts shown in Figs 9.18(a) and (b). For slope angles greater than $53^\circ$, the critical circle passes through the toe of the slope and the chart shown in Fig. 9.18(b) is used. For slope angles less than $53^\circ$,
Taylor's stability number method

In 1948, D. W. Taylor proposed a simple method of determining the minimum factor of safety for a slope in a homogeneous soil. Using a total stress analysis and ignoring the possibility of tension cracks, he produced a series of curves which relate a stability number \( N \) to the slope angle \( \beta \).

Consider the basic expression used in a total stress analysis

\[
F = \frac{c_u R L}{W_d} \quad \text{(from eqn [9.12])}
\]

It will be seen that \( L \propto H \) and \( W \propto \gamma H^2 \), i.e. \( L = K_1 H, \ W = K_2 \gamma H^2 \)

Then

\[
F = \frac{c_u R H K_1}{\gamma H^2 K_2 d}
\]

The stability number \( N \) is dependent on the geometry of the slip circle and may be defined as:

\[
N = \frac{K_2 d}{K_1 R} = \frac{c_u}{F \gamma H}
\]
(b) The effect of the tension crack is to reduce the arc length from AB to AC.

Depth of tension crack, \( z_0 = 2 \times \frac{40}{18.5} = 4.32 \text{ m} \)

Sector angle, \( \theta_c = 67.44^\circ \)

Area of slip mass, \( A = 71.64 \text{ m}^2 \)

Centroid distance from O, \( d = 5.86 \text{ m} \)

In this case, \( P_w = 0 \)

Then from eqn [9.13]:

\[
F = \frac{c_u R^2 \theta_c}{Wd}
\]

\[
= \frac{40 \times 17.43^2 \times 67.44 \times \pi}{71.64 \times 18.5 \times 5.86 \times 180}
\]

\[
= \frac{14304}{7766} = 1.84
\]

(c) When the tension crack is full of water, a horizontal force \( P_w \) will be exerted on the slip mass.

\[
P_w = \frac{1}{2} y_c z_0^2 = \frac{1}{2} \times 9.81 \times 4.32^2 = 91.54 \text{ kN/m}
\]

The lever arm of \( P_w \) about O, \( y_c = 6.7 + 2 \times 4.32/3 = 9.58 \text{ m} \)

Then from eqn [9.13]:

\[
F = \frac{c_u R^2 \theta_c}{Wd + P_w y_c}
\]

\[
= \frac{14304}{7766 + 91.54 \times 9.58} = 1.65
\]
slip circle arc and the tension crack. No shear strength can be developed in the tension crack, but, if it can fill with water, allowance must be made for the hydrostatic force $P^*$, which acts horizontally adding to the disturbing moment:

$$P^* = \frac{1}{2} \gamma_w z_o^2$$

Taking this into account, together with the fact that the slip circle arc is reduced, the factor of safety expression becomes:

$$F = \frac{c_u R^2 \theta_c}{Wd + P_w \gamma_c}$$

**Worked example 9.4**  A cutting in a saturated clay is inclined at a slope of 1 vertical:1.5 horizontal and has a vertical height of 10.0 m. The bulk unit weight of the soil is 18.5 kN/m$^2$ and its undrained cohesion is 40 kPa. Determine the factors of safety against immediate shear failure along the slip circle shown in Fig. 9.10: (a) ignoring the tension crack, (b) allowing for the tension crack empty of water, and (c) allowing for the tension crack when full of water.

The factors of safety against immediate shear failure may be obtained using the total stress method of analysis. Firstly, it is necessary to establish the geometry and area of the slip mass.

(a) In the case ignoring the tension crack, the slip mass is bounded by the ground surface and the circular arc AB, for which the following may be calculated.

Radius, \( R = OA = \sqrt{(5^2 + 16.7^2)} = 17.43 \text{ m} \)
Sector angle, \( \theta = 84.06^\circ \)
Area of slip mass, \( A = 102.1 \text{ m}^2 \)
Centroid distance from O, \( d = 6.54 \text{ m} \)

Then from eqn [9.12]:

\[
F = \frac{c_u R^2 \theta}{Wd} = \frac{40 \times 17.43^2 \times 84.06 \times \pi}{102.1 \times 18.5 \times 6.54 \times 180} = 1.44
\]
Figure 9.8 shows the cross-section of a slope together with a trial slip circle of radius $R$ and centre $O$. Instability tends to be caused due to the moment of the body weight $W$ of the portion above the slip circle.

Disturbing moment = $Wd$

The tendency to move is resisted by the moment of the mobilised shear strength acting along the circular arc $AB$.

Length of arc $\quad AB = R\theta$

Shear resistance force along $\quad AB = c_u R\theta$

Shear resistance moment $\quad = c_u R^2 \theta$

Then factor of safety, $\quad F = \frac{\text{shear resistance moment}}{\text{disturbing moment}}$

$$= \frac{c_u R^2 \theta}{Wd} \quad [9.12]$$

The values of $W$ and $d$ are obtained by dividing the shaded area into slices or triangular/rectangular segments and then taking area-moments about a vertical axis passing through the toe, or other convenient point.

**Tension cracks**

In cohesive soils, a tension crack tends to form near the top of the slope as the condition of limiting equilibrium (and failure) develops. From Chapter 8 [eqn 8.13] it will be seen that the tension crack depth may be taken as

$$z_o = \frac{2c_u}{\gamma}$$

The development of the slip circle is terminated at the tension crack depth and so its arc length is really $AC$ as shown in Fig. 9.9.
Stability of slopes

will rise and, after construction, they will gradually fall. In cuttings, however, excavation causes an initial fall in pore pressures, but as seepage develops they gradually rise. Effective stresses and therefore shear strengths are generally inversely related to pore pressures. The most critical (lowest) factor of safety may therefore be expected to occur immediately after or during the construction of an embankment; after this the soil will gradually get stronger. In contrast, the shear strength in a cutting diminishes with time and so does the factor of safety.

Thus, it is necessary to consider both short-term (end-of-construction) and long-term stability. In this context it is convenient to think of short-term conditions as being completely undrained, in which the shear strength is given by \( \tau = c_u \). In the next section, the first case to be considered will be that of undrained stability of a slope in a saturated clay; this type of analysis is often referred to as a total stress, method.

For long-term problems, and problems where changes in conditions may occur long after the end of construction (such as the sudden draw-down of level in a reservoir), a form of effective stress analysis is required. These methods may take the form of either a force- or moment-equilibrium analysis, involving plane, circular or irregular slip surfaces. For complex problems, stress path and slip line field methods are used. The shear strength parameters must be chosen with care (see Section 9.2).

9.5 Undrained stability – total stress analyses

A total stress analysis may be applied to the case of a newly cut or newly constructed slope in a fully saturated clay, the undrained shear strength being \( \tau = c_u \). It is assumed that the failure surface will take the cross-sectional form of a circular arc, usually referred to as the slip circle. The centre of the critical slip circle will be somewhere above the top of the slope. The critical (failure) slip circle is one of an infinite number of potential circles that may be drawn having different radii and centres (Fig. 9.7). Some circles will pass through the toe of the slope and some will cut the ground surface in front of the toe.

The critical circle is the one along which failure is most likely to occur and for which the factor of safety is the lowest. A number of trial circles are chosen and the analysis repeated for each until the lowest factor of safety is obtained.

![Fig. 9.7 Slip circles at different radii and centres](image-url)
The results are tabulated below for a solution in which ten slices were taken:

<table>
<thead>
<tr>
<th>Slice no.</th>
<th>( h_1 ) (m)</th>
<th>( h_2 ) (m)</th>
<th>( W ) (kN/m)</th>
<th>( x ) (m)</th>
<th>( \alpha ) (deg.)</th>
<th>( \cos \alpha - r_u \sec \alpha )</th>
<th>( N' )</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00</td>
<td>0.6</td>
<td>23.4</td>
<td>5.67</td>
<td>24.10</td>
<td>0.584</td>
<td>13.7</td>
<td>-9.6</td>
</tr>
<tr>
<td>2</td>
<td>0.00</td>
<td>2.1</td>
<td>81.9</td>
<td>4.00</td>
<td>16.70</td>
<td>0.645</td>
<td>52.8</td>
<td>-23.5</td>
</tr>
<tr>
<td>3</td>
<td>0.00</td>
<td>3.9</td>
<td>152.1</td>
<td>2.00</td>
<td>8.28</td>
<td>0.686</td>
<td>104.3</td>
<td>-21.9</td>
</tr>
<tr>
<td>4</td>
<td>0.55</td>
<td>5.0</td>
<td>214.8</td>
<td>0.00</td>
<td>0.00</td>
<td>0.700</td>
<td>150.4</td>
<td>0.0</td>
</tr>
<tr>
<td>5</td>
<td>2.00</td>
<td>4.8</td>
<td>259.2</td>
<td>2.00</td>
<td>8.28</td>
<td>0.686</td>
<td>177.8</td>
<td>37.3</td>
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<td>0.7</td>
<td>207.3</td>
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<td>46.00</td>
<td>0.265</td>
<td>54.5</td>
<td>149.0</td>
</tr>
</tbody>
</table>

\[
\Sigma N' (A \rightarrow F) = 1040 \\
\Sigma T (A \rightarrow B) = 613
\]

* Width = 2.4 m
† When \( \cos \alpha - r_u \sec \alpha < 0 \), \( N' \) is set to 0, since \( N' \) cannot be negative

\[N' = W(\cos \alpha - r_u \sec \alpha) \quad T = W \sin \alpha\]

\[L_{AF} = \theta_{AF} R = 79.9 \times \frac{\pi}{180} \times 13.39 = 19.37 \text{ m} \quad L_{FB} = 23.7 \times \frac{\pi}{180} \times 13.89 = 5.75 \text{ m}\]

Then \[F = \frac{[25 \times 5.75 + 7 \times 19.39] + [\tan 12^\circ(0) + \tan 25^\circ(1040)]}{613} = \frac{279 + 485}{613} = 1.25\]

A similar analysis carried out on a microcomputer gave \( F = 1.27 \). Another computer analysis using Bishop's simplified method gave \( F = 1.42 \).

### 9.11 Effective stress stability coefficients

A method involving the use of stability coefficients similar to that devised by Taylor, but in terms of effective stress, was suggested by Bishop and Morgenstern (1960). The factor of safety \( (F) \) is dependent on five problem variables:

(a) slope angle \( \beta \)
(b) depth factor \( D \) (as in Taylor's method – Fig. 9.18)
(c) angle of shearing resistance \( \phi' \)
(d) a non-dimensional parameter \( c'/\gamma H \)
(e) pore pressure coefficient \( r_u \)

The factor of safety varies linearly with \( r_u \) and is given by

\[F = m - nr_u\]  

\[\text{[9.19]}\]