

CHART SOLUTIONS FOR ANALYSIS OF EARTH SLOPES

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This paper compiles practical chart solutions for the slope stability problem and is concerned with the use of the solutions rather than with their derivations. Authors introduced are Taylor, Bishop and Morgenstern, Morgenstern, Spencer, Hunter, and Hunter and Schuster. Many of the solutions introduced appeared originally in publications not commonly used by highway engineers. In addition to the working assumptions and parameter definitions of each writer, the working charts are introduced, and example problems are included. The chart solutions cover a wide variety of conditions. They may be used to rapidly investigate preliminary designs and to obtain reasonable estimates of parameters for more detailed packaged computer solutions; in some cases, they may be used in the final design process.

•THE FIRST to make a valid slope stability analysis possible through use of simple charts and simple equations was Taylor (9). With the advent of high-speed electronic computers, other generalized solutions with different basic assumptions have been obtained and published. Unfortunately, these chart solutions have been published in several different sources, some of which are not commonly used by highway engineers in this country. This paper introduces several of these solutions that may prove useful and deals with how to use these solutions rather than with their derivations.

These chart solutions provide the engineer with a rapid means of determining the factor of safety during the early stages of a project when several alternative schemes are being investigated. In some cases they can be used in the final design procedure. Chart solutions such as these may very well serve as preliminary solutions for more detailed packaged computer software programs that are widely available (12).

Those chart solutions that appear to be most applicable to highway engineering problems involving stability of embankment slopes and cut slopes are presented here. In addition to introducing some solutions that may be unfamiliar, this compilation provides a quick means of locating various solutions so that rapid comparisons of advantages and disadvantages of each solution can be made.

The presentation of each solution includes pertinent references and contains sections on calculation techniques, working assumptions and definitions, limitations of the approach, and an example problem. In each case only a sufficient number of curves have been shown to indicate the scope of the charts and to illustrate the solutions. The reader should refer to the appropriate references for greater detail.

TAYLOR SOLUTION

The solution found by Taylor (9, 10) is based on the friction circle (ϕ circle) method of analysis and his resulting charts are based on total stresses. Taylor made the following assumptions for his solution:

1. A plane slope intersects horizontal planes at top and bottom. This is called a simple slope.

2. The charts assume a circular trace for the failure surface.

3. The soil is an unlayered homogeneous, isotropic material.

4. The shear strength follows Coulomb's Law so that $s = c + \tan \phi$.

5. The cohesion, c , is constant with depth as is shown in Figure 1(a).

6. Pore pressures are accounted for in the total stress assumption; therefore, seepage need not be considered.

7. If the cross section investigated holds for a running length of roughly two or more times the trace of the potential rupture surface, it is probable that this, a two-dimensional analysis, is valid.

8. The stability number in the charts is that used by Terzaghi and Peck (11) in presenting Taylor's solution. The stability number, N , is $\gamma H_c / c$.

9. The depth factor, D , as shown in Figure 2, is the depth to a firm stratum divided by the height of the slope.

The following limitations should be observed in using Taylor's solution:

1. It is not applicable to cohesionless soils.
2. It may not be applied to the partial submergence case.
3. Tension cracks are ignored.
4. According to Taylor, his analysis does not apply to stiff, fissured clays.

The charts presented by Terzaghi and Peck for Taylor's solution consist of the following:

1. A chart for soils with $\phi = 0$ deg with depth factors, D , varying from 1.0 to ∞ and slope angles, β , varying from 0 to 90 deg (Fig. 3),
2. A chart for materials having cohesion and friction with ϕ varying from 0 to 25 deg and β varying from 0 to 90 deg (Fig. 4), and
3. A chart for locating the critical circle of a slope failure (not presented in this paper).

Examples of use of Taylor's solution follow:

1. A cut is to be excavated in soft clay to a depth of 30 ft. The soil has a unit weight of 115 pcf and a cohesion of 550 psf. A hard layer underlies the soft layer at a depth of 40 ft below the original ground surface. What is the slope angle, if any, at which failure is likely to occur?

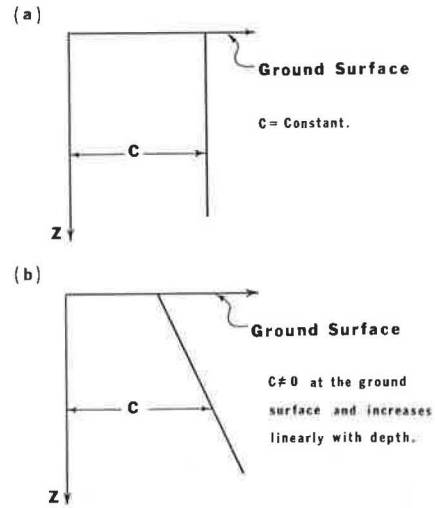


Figure 1. Comparison of assumptions for cohesion, c , as made by various investigators.

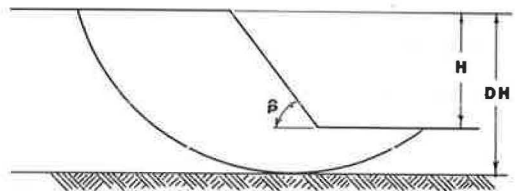


Figure 2. Elements of a simple slope.

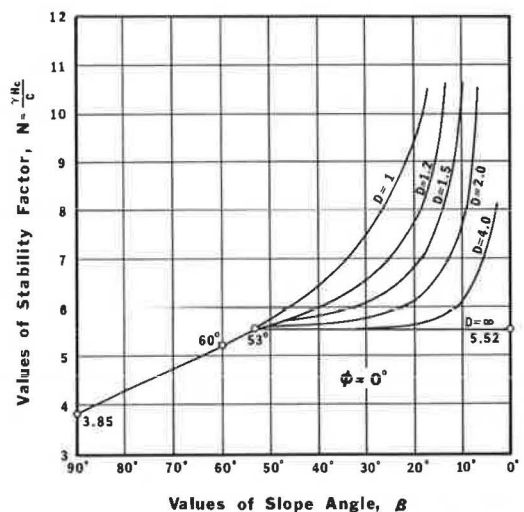


Figure 3. Relations between slope angle, β , and stability number, N , for different values of depth factor, D [after Terzaghi and Peck (11)].

Solution: Because the soil is a soft clay, ϕ is assumed to be zero and the chart of Figure 3 is applicable:

$$D = 40/30 = 1.33$$

If failure is to occur, the critical height, H_c , is 30 ft:

$$N = (\gamma H_c)/c = (115)(30)/550 = 6.28$$

From Figure 3, for $D = 1.33$ and $N = 6.28$, β may be read as 30 deg, which is the unknown that was to have been determined.

2. A cut is to be excavated in a material that has a cohesion of 250 psf, a unit weight of 115 pcf, and an angle of shearing resistance of 10 deg. The design calls for a slope angle of 60 deg. What is the maximum depth of cut that can be made and still maintain a factor of safety of 1.5 with respect to the height of the slope?

Solution: Because the soil has both cohesion and angle of shearing resistance, the chart of Figure 4 is applicable. The factor of safety (with respect to height) of 1.5 is the critical height, H_c , divided by the actual height, H . The depth factor, D , does not enter into the solution if the soil is a c, ϕ type of soil.

From Figure 4, for $\phi = 10$ deg and $\beta = 60$ deg, N may be read as 7.25. From the definition of stability number,

$$N = (\gamma)(H_c)/c$$

or

$$H_c = (c)(N)/\gamma = (250)(7.25)/115 = 15.75 \text{ ft}$$

$$H = H_c/1.5 = 15.75/1.5 = 10.5 \text{ ft}$$

Thus, it would be possible to make a 60-deg cut at any depth up to 10.5 ft and still maintain a factor of safety that is equal to or greater than 1.5.

BISHOP AND MORGENSTERN SOLUTION

Bishop's adaptation of the Swedish slice method (1) was used by Bishop and Morgenstern (2) for their solution. Their charts are based on effective stresses rather than total stresses. Consequently, it is necessary to take pore pressures into consideration.

Bishop and Morgenstern made the following assumptions:

1. The geometry of the slope is simple, as was the case for Taylor's solution. The potential sliding surface is assumed to be cylindrical; the trace of the sliding surface is assumed to be a portion of a circle.

2. The pore pressure is accounted for by use of the pore pressure ratio, r_u . This ratio is defined as being equal to $u/(\gamma h)$, where h = depth of point in soil mass below the soil surface, γ = unit weight of the soil (bulk density), and u = pore pressure of water in the soil. The pore pressure ratio is assumed to be constant throughout the cross section; this is called a homogeneous pore pressure distribution. If there are minor variations in r_u throughout the cross section, an average value of r_u can be used.

3. For steady-state seepage, use a weighted average of r_u over the section.

4. The factor of safety, FS, is defined as $m - (n)(r_u)$, where m and n are determined by using charts in Figures 5 through 7.

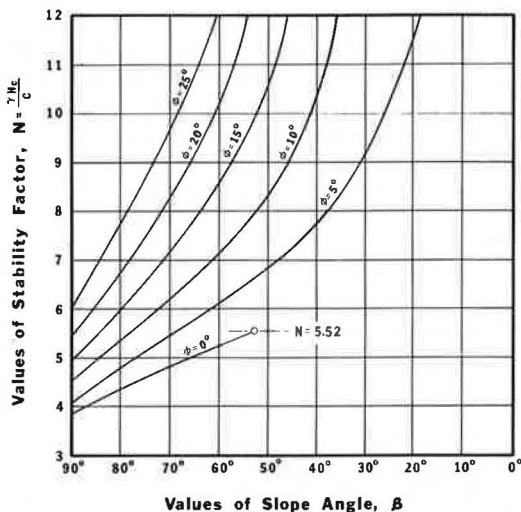


Figure 4. Relations between slope angle, β , and stability number, N , for materials having cohesion and friction, for various values of ϕ [after Terzaghi and Peck (11)].

5. Depth factors, D , of 1.0, 1.25, and 1.5 are used in this solution where the depth factor is defined as Taylor defined it: The depth to a hard stratum is the depth factor multiplied by the embankment height.

6. The solution implies that the cohesion is constant with depth as shown in Figure 1(a). An interesting feature of this solution is that pore pressures can be changed to see what effect this will have on the stability of the slope.

Bishop and Morgenstern's solution has the following limitations:

1. There is no provision for intermediate water table levels.
2. The averaging technique for pore pressure ratio tends to give an overestimation of the factor of safety. In an extreme case, this overestimation will be on the order of 7 percent.

In using this chart solution it is convenient to select the critical depth factor by use of the lines of equal pore pressure

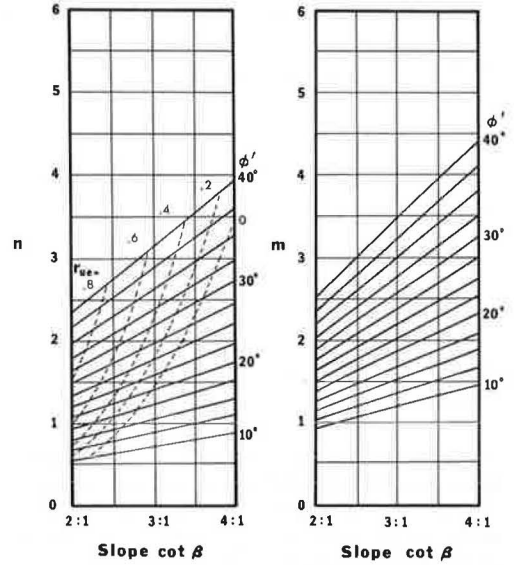


Figure 5. Stability coefficients, m and n , for $\frac{c'}{\gamma H} = 0.05$ and $D = 1.00$ [after Bishop and Morgenstern (2)].

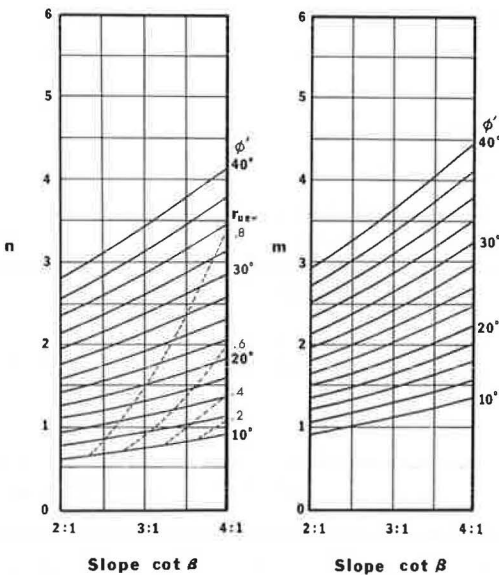


Figure 6. Stability coefficients, m and n , for $\frac{c'}{\gamma H} = 0.05$ and $D = 1.25$ [after Bishop and Morgenstern (2)].

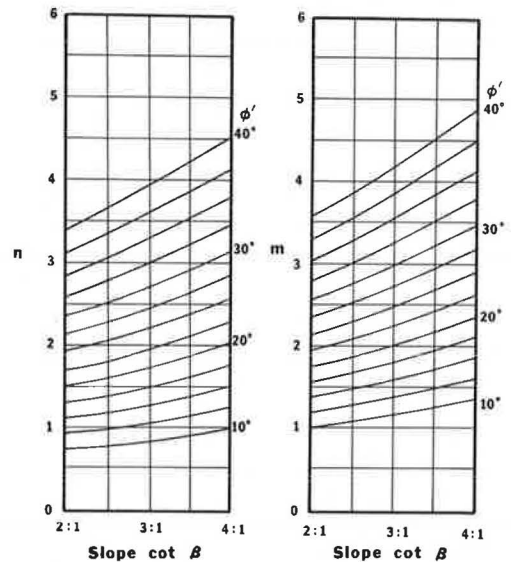


Figure 7. Stability coefficients, m and n , for $\frac{c'}{\gamma H} = 0.05$ and $D = 1.50$ [after Bishop and Morgenstern (2)].

ratio, r_{ue} , on the charts of Figures 5 and 6. The ratio, r_{ue} , is defined as $(m_2 - m_1)/(n_2 - n_1)$ where n_2 and m_2 are values for a higher depth factor, D_2 , and n_1 and m_1 correspond to a lower value of the depth factor, D_1 .

If the design value of pore pressure ratio is higher than r_{ue} for the given section and strength parameters, then the factor of safety determined with the higher depth factor, D_2 , has a lower value than the factor of safety determined with the lower depth factor, D_1 . This is useful to know when no hard stratum exists or when checking to see if a more critical circle exists not in contact with a hard stratum. The example problem will clarify this concept.

To determine the minimum factor of safety for sections not located directly on a hard stratum, enter the appropriate chart for the given $c'/(\gamma H)$ and, initially, for $D = 1.00$. Note that c' is the effective stress value of cohesion and H is the height of the slope while γ is the unit weight of the soil. The values of β and ϕ' define a point on the curves of n with which is associated a value of r_{ue} given by the dashed lines. If that value is less than the design value of r_u , the next depth factor, $D = 1.25$, will yield a more critical value of the factor of safety. If, from the chart for $D = 1.25$, the values are checked and r_{ue} is still less than the design value for r_u , move to the chart for $D = 1.50$ with the same value of $c'/(\gamma H)$.

Bishop and Morgenstern (2) show charts for values of $c'/(\gamma H)$ of 0.00, 0.025, and 0.05 with depth factor, D , values of 1.00, 1.25, and 1.50. Only enough charts are shown here to illustrate the solution.

An example of Bishop and Morgenstern's solution follows:

A slope is cut so that the cotangent of the slope angle, β , is 4.0. The cut is 140 ft deep. A hard stratum exists at a depth of 60 ft below the bottom of the cut. The soil has an effective angle of shearing resistance, ϕ' , of 30 deg. The effective cohesion, c' , is 770 psf. The unit weight is 110 pcf, and it is estimated that the pore pressure ratio, r_u , is 0.50 for the slope.

From the given conditions, $c'/(\gamma H) = 770/(110)(140) = 0.050$. From Figure 5, for $D = 1.00$ with $c'/(\gamma H) = 0.050$, $\phi' = 30$ deg, and $\cot \beta = 4.0$, it is seen that $r_{ue} < 0.5$. Therefore, $D = 1.25$ is the more critical value for depth factor. Using Figure 6, with the same value of $c'/(\gamma H)$ and with $D = 1.25$, it is found that $r_{ue} > 0.5$. In this case the maximum value that D could have is $(140 + 60)/140 = 1.43$. Therefore, within the limitations of the charts, $D = 1.25$ is the critical depth factor. From Figure 6 it is seen that $m = 3.22$ and $n = 2.82$ for the given values of $c'/(\gamma H)$, ϕ' , and $\cot \beta$. Accordingly, the following factor of safety is obtained:

$$FS = m - (n)(r_u) = 3.22 - 2.82(0.50) = 1.81$$

The chart for $D = 1.50$ for $c'/(\gamma H) = 0.050$ (Fig. 7) is not necessary for the solution to this example problem, but it is given to indicate the range in this particular sequence of charts.

MORGENSTERN SOLUTION

Morgenstern (6) used Bishop's adaptation of the Swedish slice method of analysis (1) to develop a solution to the slope stability problem that is somewhat different from the one he developed with Bishop. His solution is, again, based on effective stresses rather than total stresses. His solution is primarily for earth dams, but there are highway cuts and fills that nearly fulfill his assumptions. Morgenstern made the following assumptions:

1. The slope is a simple slope of homogeneous material resting on a rigid impermeable layer at the toe of the slope.
2. The soil composing the slope has effective stress parameters c' (cohesion) and ϕ' (angle of shearing resistance), both of which remain constant with depth.
3. The slope is completely flooded prior to drawdown; a full submergence condition exists.

4. The pore pressure ratio $\bar{\beta}$, which is $\Delta u / \Delta \alpha_1$, is assumed to be unity during drawdown, and no dissipation of pore pressure occurs during drawdown.

5. The unit weight of the soil (bulk density), γ , is assumed to be constant at twice the unit weight of water of 124.8 pcf.

6. The pore pressure can be approximated by the product of the height of soil above a given point and the unit weight of water.

7. The drawdown ratio is defined as L/H where L is the amount of drawdown and H is the original height of the slope.

8. To be consistent, all assumed potential sliding circles must be tangent to the base of the section. This means that the value of H in the stability number, $c'/(\gamma H)$, and in L/H must be adjusted for intermediate levels of tangency (see the example problem for clarification).

Morgenstern's solution is particularly good for small dams and consequently might be particularly applicable where a highway embankment is used as an earth dam or for flooding that might occur behind a highway fill. Another important attribute of the method is that it permits partial drawdown conditions.

This method is somewhat limited by its strong orientation toward earth dams. If a core exists, it is noted that this violates the assumption of a homogeneous material. Another limitation is the assumption that the unit weight is fixed at 124.8 pcf. Attention is also called to the assumption of an impermeable base.

Morgenstern's charts cover a range of stability numbers, $c'/(\gamma H)$, from 0.0125 to 0.050 and slopes of 2:1 to 5:1. The maximum value of ϕ' shown on his charts is 40 deg. Following are some example problems using Morgenstern's method:

1. An embankment has a height, H , of 100 ft. It is composed of a soil with an effective cohesion, c' , of 312 psf and an effective angle of shearing resistance, ϕ' , of 30 deg. The unit weight of the soil must be assumed to be equal to 124.8 pcf. The embankment is to have a slope so that the cotangent of the slope angle is 3.0. What is the minimum factor of safety for the complete drawdown condition?

Solution: The stability number, $c'/(\gamma H) = 312 / [(124.8)(100)] = 0.025$. With this value and with $\cot \beta = 3.0$, $\phi' = 30$ deg, and the drawdown ratio $L/H = 1.0$, the factor of safety is directly obtainable from Figure 9 as $FS = 1.20$. By examining the charts in Figures 8 through 10, it can be seen that the critical circle is tangent to the base of the slope;

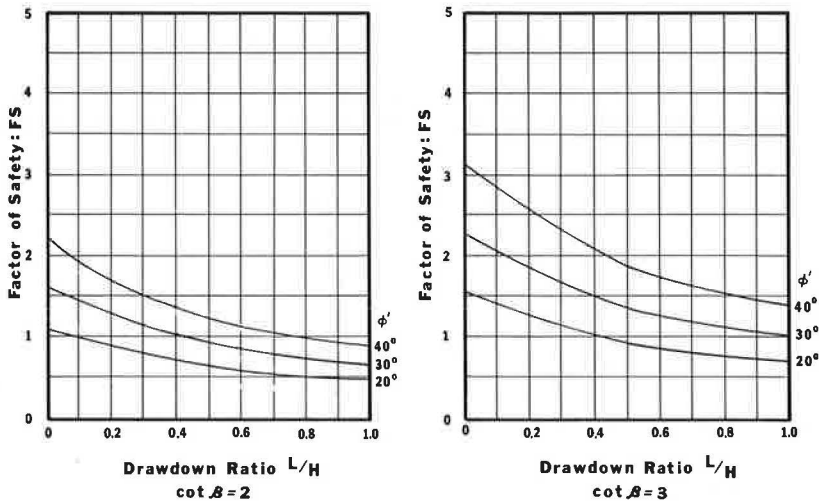


Figure 8. Relationship between factor of safety, FS , and drawdown ratio, L/H , for

$$\frac{c'}{\gamma H} = 0.0125 \text{ [after Morgenstern (6)]}.$$

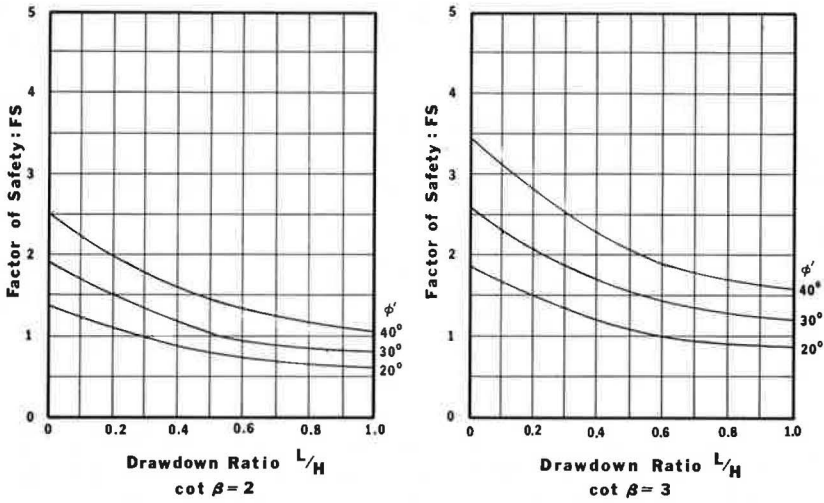


Figure 9. Relationship between factor of safety, FS, and drawdown ratio, L/H , for $\frac{c'}{\gamma H} = 0.025$ [after Morgenstern (6)].

if any other tangency is assumed, H would have to be reduced. If H is reduced, then the stability number is increased and this will, in all cases, result in a higher factor of safety.

2. It is now required to find the minimum factor of safety for a drawdown to mid-height of the section in the prior example.

Solution a: Considering slip circles tangential to the base of the slope, the effective height of the section, H_e , is equal to its actual height and the stability number remains

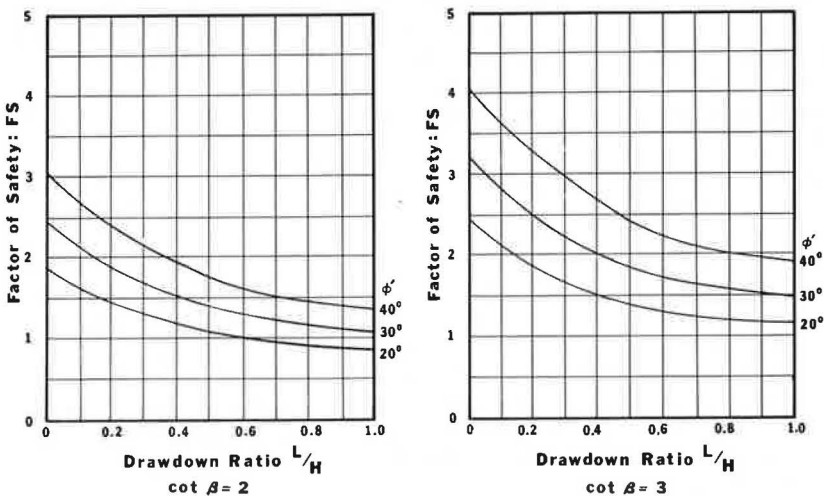


Figure 10. Relationship between factor of safety, FS, and drawdown ratio, L/H , for $\frac{c'}{\gamma H} = 0.050$ [after Morgenstern (6)].

unchanged as 0.024. With this value of stability number and $L/H_e = 0.50$, and with other conditions remaining the same, the factor of safety may be read from Figure 9 as $FS = 1.52$.

Solution b: Considering slip circles tangential to mid-height of the slope, the effective height is equal to one-half the actual height so that $H_e = H/2 = 100/2 = 50$ ft. Thus $c'/(\gamma H_e)$ is twice that of the previous solution or 0.05, and $L/H_e = 1.00$. The minimum factor of safety, as determined by Morgenstern's solution, can be read directly from Figure 10 as $FS = 1.48$.

Solution c: Considering slip circles tangential to a level $H/4$ above the base of the slope, H_e becomes $3H/4 = 75$ ft. Thus the stability number $c'/(\gamma H_e) = 0.033$, and $L/H_e = 0.67$. The minimum factor of safety for this family must be obtained by interpolation. From Figure 9 with $c'/(\gamma H_e) = 0.025$, the factor of safety is 1.31, and from Figure 10 with $c'/(\gamma H_e) = 0.05$, the factor of safety is 1.61. Interpolating linearly for $c'/(\gamma H_e) = 0.033$, the minimum factor of safety for this family is $1.31 + 0.30/3 = 1.41$.

These examples demonstrate that for partial drawdown the critical circle may often lie above the base of the slope, and it is important to investigate several levels of tangency for the maximum drawdown level. In the case of complete drawdown, the minimum factor of safety is always associated with circles tangent to the base of the slope and the factor of safety at intermediate levels of drawdown need not be investigated. This may not be the case if the pore pressure distribution during drawdown differs significantly from that assumed by Morgenstern.

SPENCER SOLUTION

Bishop's adaptation of the Swedish slice method has been used by Spencer (8) to find a generalized solution to the slope stability problem. Spencer assumed parallel interslice forces. His solution is based on effective stresses. Spencer defines the factor of safety, FS , as the quotient of shear strength available divided by the shear strength mobilized.

Spencer made the following additional assumptions and definitions for his solution:

1. The soils in the cut or embankment and underneath the slope are uniform and have similar properties.
2. The slope is simple and the potential slip surface is circular in profile.
3. A hard or firm stratum is at a great depth, or the depth factor, D , is very large.
4. The effects of tension cracks, if any, are ignored.
5. A homogeneous pore pressure distribution is assumed with the pore pressure coefficient, r_u , equal to $u/(\gamma h)$, where u = mean pore water pressure on base of slice, γ = unit weight of the soil (bulk density), and h = mean height of a slice.
6. The stability number N is defined as $c'/[(FS)\gamma H]$.
7. The mobilized angle of shearing resistance, ϕ'_m , is the angle whose tangent is $(\tan \phi')/FS$.

Spencer's method does not prohibit the slip surface from extending below the toe. His solution permits the safe slope for an embankment of a given height to be found rapidly.

Although the limitations of Spencer's method are few, it is noted that a simple trial and error solution is required to find the factor of safety with the slope and soil properties known. In addition, it is difficult to use his method for intermediate levels of the water table. Spencer provides charts for a range of stability number, N , from 0.00 to 0.12 with mobilized angle of shearing resistance varying from 10 to 40 deg and slope angles up to 34 deg. Charts are provided for pore pressure ratio, r_u , with values of 0.0, 0.025, and 0.50. Only one of these charts (Fig. 11) is shown for use in the example problem. Spencer furnishes charts for locating the critical surface.

An example of Spencer's solution follows:

An embankment is to be formed with a factor of safety of 1.5 and a height of 100 ft. The soil has an effective cohesion of 870 psf and an effective angle of shearing resistance of 26 deg. The unit weight of the soil is 120 pcf and the pore pressure ratio is 0.50. Find the slope that corresponds to this factor of safety.

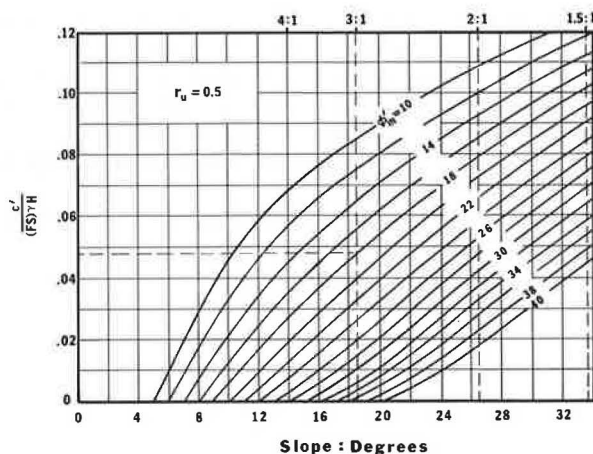


Figure 11. Relationship between stability number $\left[\frac{c'}{(FS) \gamma H} \right]$ and slope angle, β , for various values of ϕ'_m [after Spencer (8)].

Solution: The stability number,

$$N = c' / [(FS) \gamma H] = 870 / [(1.5)(120)(100)] = 0.048$$

$$\tan \phi'_m = (\tan \phi') / FS = \tan 26 \text{ deg} / 1.5 = 0.488 / 1.5$$

$$\tan \phi'_m = 0.325 \text{ or } \phi'_m = 18 \text{ deg}$$

Referring to Figure 11 for $r_u = 0.50$, the slope corresponding to a stability number of 0.48 and $\phi'_m = 18 \text{ deg}$ is $\beta = 18.4 \text{ deg}$. This corresponds approximately to a slope of 3:1.

Linear interpolation between charts for slopes for r_u values falling between the chart values is probably sufficiently accurate.

HUNTER SOLUTION

In 1968, Hunter (3) approached the slope stability problem with two assumptions that are different from the solutions previously presented in this paper. He assumed that the trace of the potential slip surface is a logarithmic spiral and the cohesion varies with depth. His charts are based on total stresses. Hunter's working assumptions and definitions follow:

1. The section of a cut is simple with constant slope, and top and bottom surfaces are horizontal.
2. The soil is saturated to the surface through capillarity.
3. The soil is normally consolidated, unfissured clay.
4. The problem is two-dimensional.
5. The shear strength can be described as $s = c + p \tan \phi$ where c varies linearly with depth, as is shown in Figure 1(b). It is assumed that the ratio c/p' is a constant, where p' is the effective vertical stress. Note that p' increases with depth.
6. If $\phi > 0 \text{ deg}$, the potential slip surface is a logarithmic spiral. If $\phi = 0 \text{ deg}$, the potential failure surface is a circle because the logarithmic spiral degenerates into a circle for this case.

7. The effective stresses immediately after excavation are the same as those before excavation. This describes the end-of-construction case.

8. The water table ratio, M , is defined as $(h/H)(\gamma_w/\gamma')$, where h = depth from top of slope to the water table during consolidation, H = height of cut, γ_w = unit weight of water, and γ' = submerged or buoyant unit weight of soil.

9. While c increases linearly with depth, the angle of shearing resistance, ϕ , is constant with depth.

10. A stability number, N , is obtained so that the factor of safety,

$$FS = \frac{c}{\gamma z_1 N}$$

where

$$z_1 = z + h \left(\frac{\gamma_w}{\gamma'} \right)$$

and z = depth below the original ground surface of cut to point where cohesion, c , is determined.

An equivalent and perhaps more convenient relationship is

$$FS = \left(\frac{c}{p'} \right) \left(\frac{\gamma'}{\gamma} \right) N$$

because often (c/p') can be estimated from Skempton's (7) formula,

$$\left(\frac{c}{p'} \right) = 0.11 + 0.0037(PI)$$

where PI = plasticity index of the soil in percent.

11. The depth ratio, D , is defined the same as in the description of Taylor's work. If $\phi > 0$ deg, the effects of a firm layer at any depth are negligible. If $\phi = 0$ deg, the depth factor can have a significant but small influence on the factor of safety, as is shown in Hunter's (3) work and also by Hunter and Schuster (4). Only when the stability number, N , is greater than about 25 and the slope angle, β , is less than about 15 deg is the small reduction in N important enough to be taken into account.

Hunter's solution permits realistic variation in the values of cohesion, c , for normally consolidated soils. It can easily handle the situation for the water table at any of a wide range of elevations. This solution should be used only for normally consolidated materials.

Numerous charts are furnished by Hunter. The charts show the slope angle, β , varying from 5 to 90 deg, and the angle of shearing resistance ϕ varying from 0 to 35 deg in steps of 5 deg. The water table ratio, M , is varied from 0.00 to 2.00 in steps of 0.25. In addition, many tables and graphs are shown that are useful in locating the critical failure surface. In this paper only one chart (Fig. 12) is shown to illustrate Hunter's solution. An example of Hunter's solution follows:

A 25-ft slope of 30 deg is to be cut in normally consolidated material with a unit weight of 112 pcf and the water table at a depth of 10 ft. The material has been tested (on a total stress basis) and found to have a ϕ of 10 deg with a plasticity index of 25 percent. It is required to estimate the factor of safety of this slope.

Solution: Using Skempton's relationship,

$$c/p' = 0.11 + 0.0037(PI) = 0.11 + 0.0037(25) = 0.2025$$

$$M = \left(\frac{h}{H} \right) \left(\frac{\gamma_w}{\gamma'} \right) = \left(\frac{10}{25} \right) \left(\frac{62.4}{112 - 62.4} \right) = \left(\frac{10}{25} \right) (1.26) = 0.502$$

Using $M = 0.50$, $\beta = 30$ deg, and $\phi = 10$ deg, find the stability number from the chart in Figure 12. Read $N = 17.1$. Thus, the factor of safety,

$$FS = \left(\frac{c}{p'} \right) \left(\frac{\gamma'}{\gamma} \right) N$$

$$FS = (0.2025) \left(\frac{49.6}{112} \right) (17.1) = 1.52$$

HUNTER AND SCHUSTER SOLUTION

Based on some of Hunter's original work (3), Hunter and Schuster (4) published a solution for the special case of $\phi = 0$ deg in normally consolidated clays. This solution is a total stress solution.

The assumptions are the same as those made by Hunter in the previous section, except that the potential sliding surface is a circular arc rather than a logarithmic spiral. In particular, this solution permits the cohesion, c , to increase linearly with depth, and the saturated soil may have a water table that can be anywhere within a wide range. The depth factor, D , is taken into account. The method ignores tension cracks.

The charts furnished by Hunter and Schuster show the water table ratio varying from 0.00 to 2.00 in steps of 0.25, and the depth ratio, D , varying from 0 to 4. Only those charts (Figs. 13 and 14) necessary to illustrate the example problem are shown. Some example problems using Hunter and Schuster's solution follow:

1. A cut 15 ft deep is to be made in a normally consolidated clay with a slope angle of 30 deg. The water table is 5 ft below the original ground surface. The soil weighs 104 pcf, and the c/p' ratio is 0.24 for the soil. What is the factor of safety for this cut?

Solution: The water table ratio M is

$$M = \left(\frac{h}{H} \right) \left(\frac{\gamma_w}{\gamma'} \right) = \left(\frac{5}{15} \right) \left(\frac{62.4}{41.6} \right) = 0.50$$

In Figure 13, with $M = 0.50$ and $\beta = 30$ deg, $N = 8.9$ (a possible shallow failure). Calculate the factor of safety, FS , as

$$FS = \left(\frac{c}{p'} \right) \left(\frac{\gamma'}{\gamma} \right) N = (0.24) \left(\frac{41.6}{104} \right) (8.9) = 0.855 < 1.00$$

It can therefore be concluded that this cut is impossible without failure occurring.

2. A cut at a slope angle of 10 deg is to be made 15 ft deep in a normally consolidated clay with the water table 15 ft from the surface. Underneath the clay at a depth of 30 ft is a harder, stronger stratum. When tested, the soil showed $\phi = 0$ deg on a total stress basis. The ratio c/p' for this soil is 0.24, and its unit weight is 104 pcf. Find the factor of safety for this proposed cut.

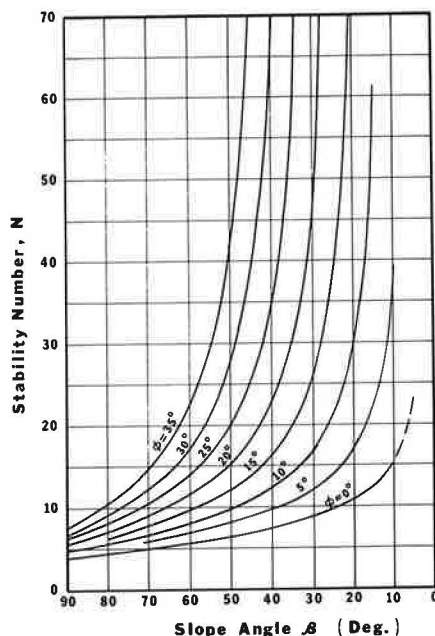


Figure 12. Relationship between slope angle and stability number, N , for $M = 0.50$ and unlimited depth of soil, for various values of ϕ . Solid lines indicate shallow surfaces and dashed lines indicate deep surfaces [from Hunter (3)].

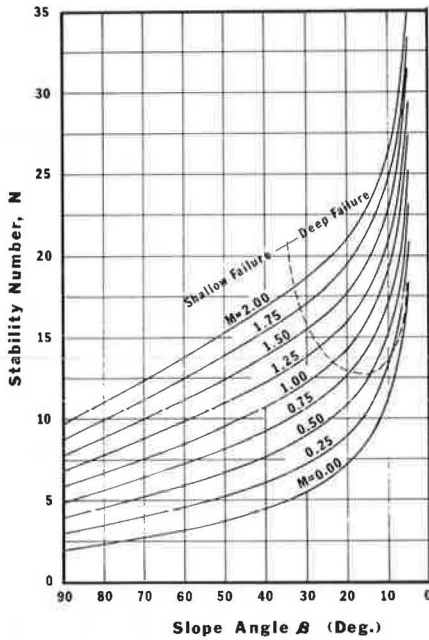


Figure 13. Relationship between slope angle, β , and stability number, N , for $\phi = 0$ and unlimited depth of clay [from Hunter and Schuster (4)].

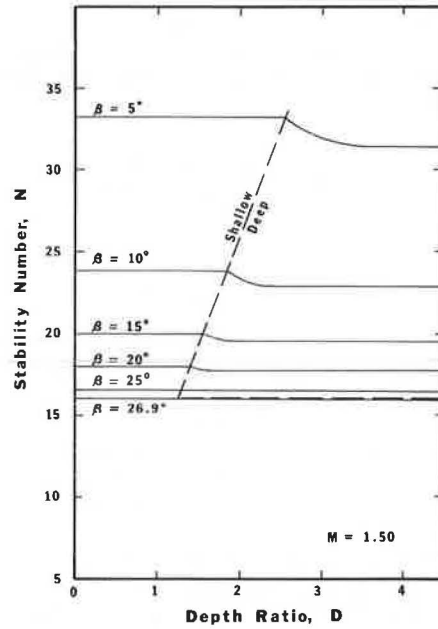


Figure 14. Relationship between depth factor, D , and stability number, N , for $\phi = 0$ for selected values of slope inclination [from Hunter and Schuster (4)].

Solution:

$$M = \left(\frac{h}{H} \right) \left(\frac{\gamma_w}{\gamma'} \right) = \left(\frac{15}{15} \right) \left(\frac{62.4}{41.6} \right) = 1.50$$

From Figure 13, with $\beta = 10$ deg and $M = 1.50$, the value of N plots up in the deep failure zone with a value of approximately 23.9. Because it is in the deep failure zone, $D = 30/15 = 2.0$ may be important.

From Figure 14, for $M = 1.50$, $D = 2.0$, and $\beta = 10$ deg, it is seen that N reduces slightly to 23.2. Thus, the factor of safety is

$$FS = \left(\frac{c}{p'} \right) \left(\frac{\gamma'}{\gamma} \right) N = (0.24) \left(\frac{41.6}{104} \right) (23.2) = 2.23$$

Note that the depth factor, in general, has only a negligible or quite small effect on the factor of safety.

One set of generalized solutions that should be mentioned is that developed by Janbu (5). His solutions are extensive and do not lend themselves to simple presentations as has been the case with the other solutions. Janbu's solutions are useful in analyzing the influence of drawdown conditions and the effect of water-filled tension cracks and surcharge. Janbu implies that both the cohesion, c , and the angle of shearing resistance, ϕ , are constant with depth. Although not reviewed here, Janbu's solutions are recommended to the engineer who frequently deals with stability analyses of slopes.

SUMMARY

The chart solutions developed by Taylor, Bishop and Morgenstern, Morgenstern, Spencer, Hunter, and Hunter and Schuster can be applied to a number of types of slope stability analyses. Some of the methods presented were originally developed only for cuts; some were developed especially for embankments or fills such as earth dams. Each solution presented, however, is applicable to some highway engineering situation. References have been given indicating more complex chart solutions not illustrated here, and an entry into the literature on computerized solutions has been given. Of the solutions introduced, those of Taylor, Hunter, and Hunter and Schuster are best suited to the short-term (end-of-construction) cases where pore pressures are not known and total stress parameters apply. The other methods are intended for use in long-term stability (steady seepage) cases with known effective stress parameters.

The methods make similar assumptions regarding slope geometry, two-dimensional failure, and the angle of shearing resistance being constant with depth. However, they vary considerably in assumptions regarding variation of cohesion, c , with depth, position of the water table, base conditions, drawdown conditions, and shape of the failure surface. Altogether, a wide range of conditions can be approximated by these available generalized solutions.

Each author has attempted to reduce the calculation time required to solve stability problems. The chart solutions alone may be sufficient for many highway problems; in other cases, chart solutions may save expensive computer time by providing a reasonable estimate as a starting point for computer programs that solve slope stability problems.

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