An Appraisal of Measures for Improvement of Slope Stability[1]

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Generally, attempts to increase the factor of safety of an earth slope involve either drainage or excavation. The object of drainage is a lowering of the water table, with an accompanying reduction in the magnitude of unfavorable forces. In the present paper several graphs are presented which enable the engineer to estimate the amount of drainage necessary to achieve a desired factor of safety. These graphs yield safety factors corresponding to various levels of water table in an earth mass where the failure plane would approximate a Swedish arc located in a clay bank underlain by a permeable stratum.

An alternative procedure improves stability by unloading the slope. It is shown that flattening the slope is much less effective than benching per unit of excavation. Graphs are presented which plot factor of safety against quantity of excavation for both benching and slope reduction. Both $\phi = 0$ and $\phi > 0$ Cases are considered.

● WHEN THE STABILITY of an earth mass is deemed to be unsatisfactory, the engineer entrusted with the task of improving the stability of the slope will elect, generally, either to flatten the slope or to drain the unstable bank. Existing methods of analysis are adequate for the determination of the factor of safety of the bank both before and after the execution of the measures taken for the betterment of stability. The objective of the present paper is to extend the application of existing analytical procedures to the point where an engineer may design his landslide control measures to achieve a preselected factor of safety, rather than by trial and error determine the factor of safety of a tentative design.

REMEDIAL EXCAVATION

The increase in stability can be achieved by flattening a clay bank is illustrated in Figure 1. It is assumed that seepage forces are negligible in a mass of medium clay 40 ft high. The pertinent soil properties are:

unit weigth, γ = 120 lb per cu ft
cohesion, c = 1000 lb per sq ft, and
friction, ϕ = 6 deg

It is evident that flattening this slope (increasing the value of b) serves to increase the factor of safety. If a rise of 1 ft is

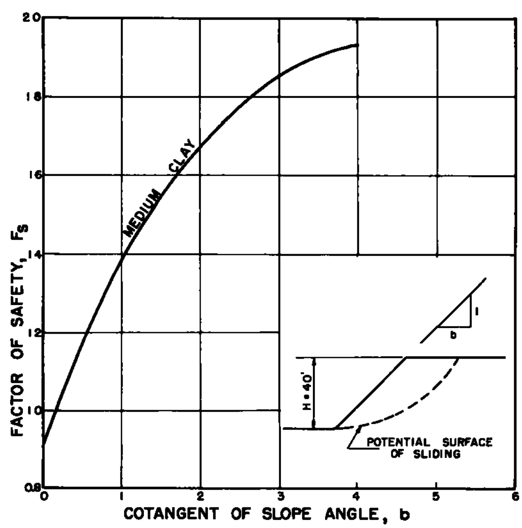

Figure 1.

[1] This paper is based on two MSCE theses: "The Effect of Drainage in Landslide Control," by Eugene L. McCoy (1955); and "Slope Deformation and Safety as Related to Railway Landslide Problems," by Sidney E. Hawkins (1955). The research was supervised by R. G. Hennes.

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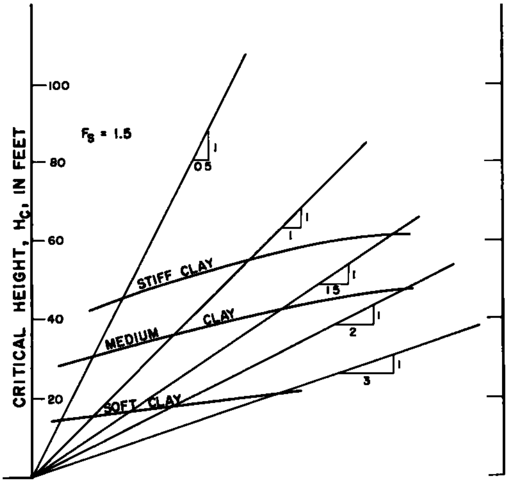


Figure 2.

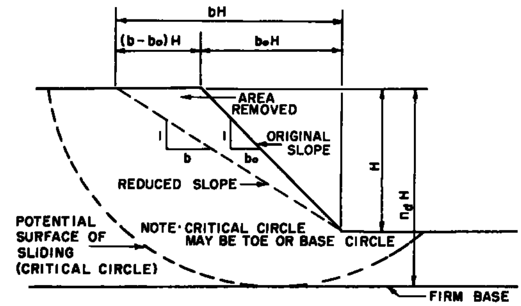


Figure 3.

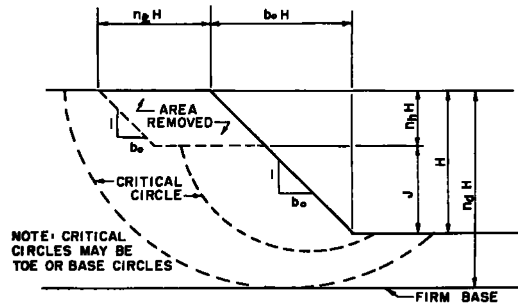


Figure 4.

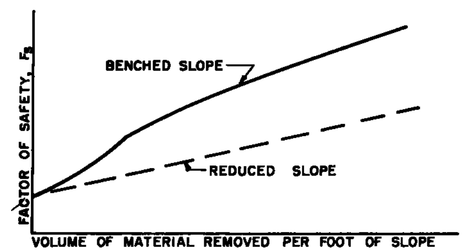


Figure 5.

achieved in a horizontal run of 2 ft instead of 1 ft, the factor of safety is increased from about 1.38 to about 1.67.

More information on the relationship between slope angle and stability is presented in Figure 2, which shows the critical heights corresponding to various slope angles in specific soils. Conventionally, critical height is the maximum height at which a bank will stand (factor of safety of unity) at a given slope angle. However, Figure 2 is based upon a factor of safety equal to 1.5 rather than unity, as a more useful value. The assumed properties of the selected clays are:

	Stiff	Medium	Soft
γ =	130	120	110 pcf
c =	1500	1000	400 psf
ϕ =	8 deg	6 deg	4 deg

It is noteworthy that slope angle is not a dominant factor in the stability of the more plastic clay banks.

Both Figures 1 and 2 were derived from curves showing the stability factor, N_s, for different slope angles and different soil properties by N. Janbu (1). N_s is a pure number showing how stable a slope is for a particular homogeneous earth material. The factor of safety, F_s, as used on these plates is found by

$$F_s = N_s \frac{C}{\gamma H}$$

in which

c = cohesion of soil in lb/ft^2
γ = unit wt of soil in lb/ft^3
H = height of slope

Janbu's curves give information similar to the stability curves presented by D. W. Taylor (2). However, factors of safety derived from Taylor's curves will generally be somewhat higher.

Reduction of Slope Angle. A procedure for removing material is to reduce the slope

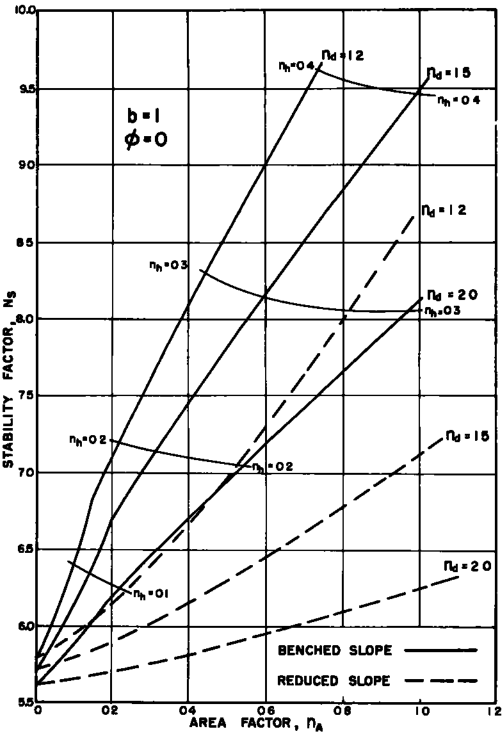


Figure 6.

angle as in Figure 3. Referring back to Figures 1 and 2, it is evident that this procedure would increase the slope safety.

Already one objection to decreasing the slope angle has been mentioned. In addition, for large reduction of the slope angle, new right-of-way would be required to accommodate the flatter slope. Later discussion will also reveal that this method is not the most economical with respect to the amount of material moved.

Benching. A second method for unloading a slope is benching. Here the material near the crest of the slope is removed, leaving a bench part way down the slope. This type of removal takes material from the part of the slope where it will do the most good. Figure 4 is a cross-section of a benched slope.

The benching method is more effective because material is removed from the upper part of the slope. All of the material in this location provides a large driving force to produce slope failure.

Figure 5 shows the increase in factor of safety due to benching and slope reduction. Both curves start from the same point which is the factor of safety for the original slope prior to unloading by either

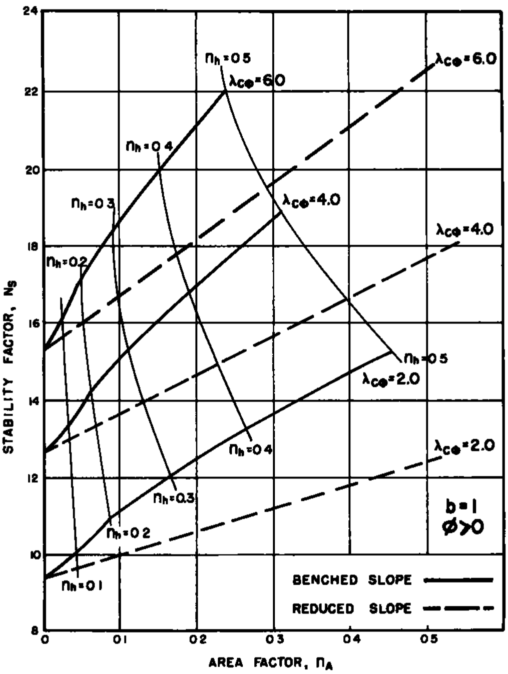


Figure 7.

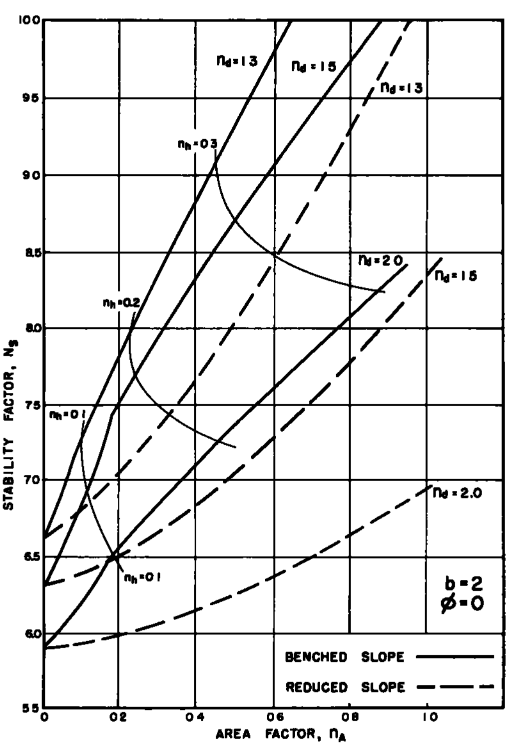


Figure 8.

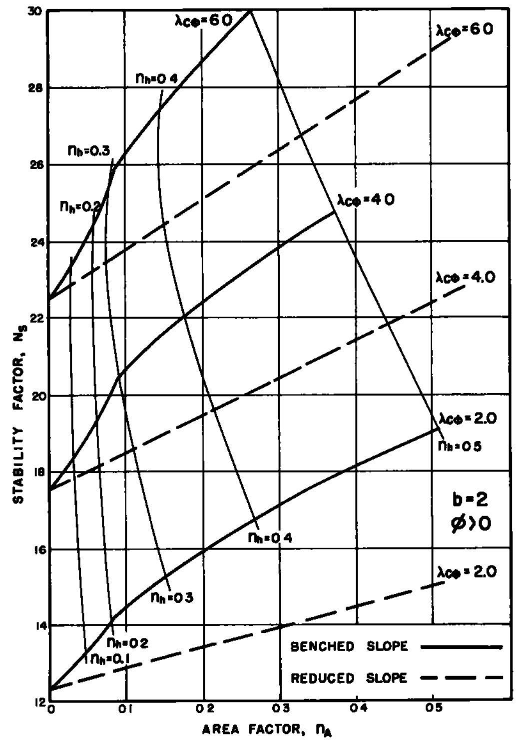
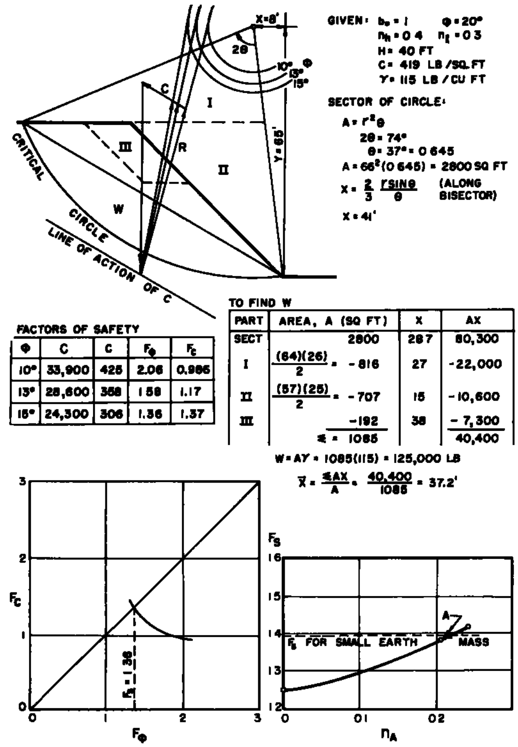


Figure 9.



FACTORS OF SAFETY

φ	C	c	F_ϕ	F_c
10°	33,900	425	2.06	0.986
13°	28,600	358	1.58	1.17
15°	24,300	306	1.36	1.37

TO FIND W

PART	AREA, A (SQ FT)	X	AX
SECT	2800	287	80,300
I	$\frac{(64)(26)}{2} = -816$	27	-22,000
II	$\frac{(57)(25)}{2} = -707$	15	-10,600
III	-192	38	- 7,300
	Σ = 1085		40,400

$W = A\gamma = 1085(115) = 125{,}000$ LB

$\bar{X} = \frac{\Sigma AX}{A} = \frac{40{,}400}{1085} = 37.2'$

Figure 10.

method. The increase in F_S due to benching is achieved by lowering and widening the bench. F_S will increase until the bench is halfway down the slope. Any further lowering will not increase F_S. The proper relationship between depth and width of the bench can be obtained from curves to follow.

As shown in Figure 5, the safety of a slope can be increased any set amount for less excavation by benching than by slope reduction. The results of this study also show that the greater the soil strength the less is the excavation required to produce a given increase in F_S by benching or slope reduction.

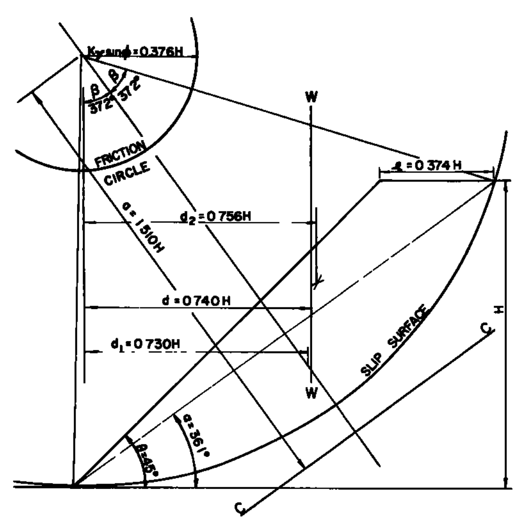
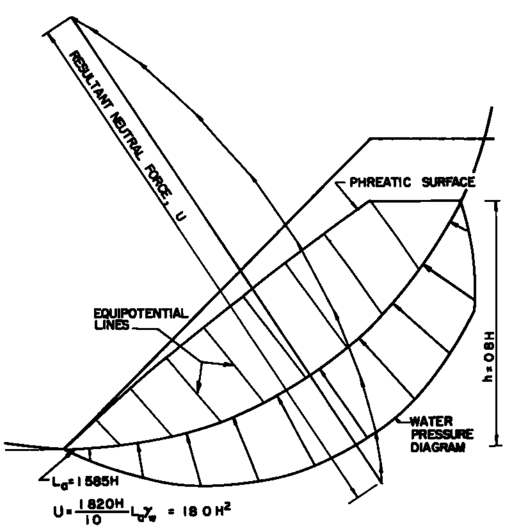


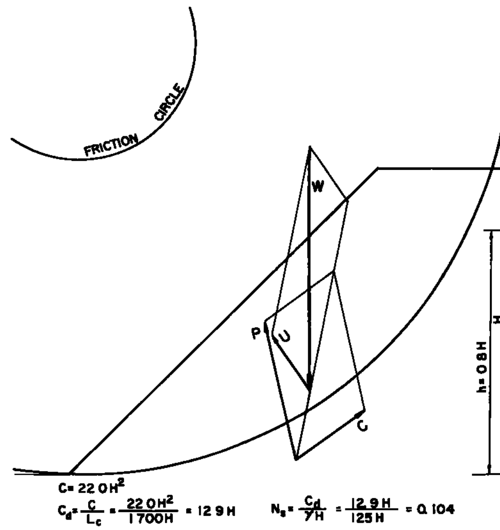
Figure 11.

To aid in the determination of the proper bench dimensions and to compare the benching and slope reduction methods, the curves in Figure 6 through 9 have been prepared. They pertain only to slopes of homogeneous earth material with negligible seepage forces. These curves are in general the same as found in Figure 5 except F_S has been replaced by N_S, the dimensionless stability factor already mentioned. This group of curves includes original slopes of 1 to 1 and 2 to 1. Figures 6 and 8 are for purely cohesive soils such as clays in which the angle of internal friction is zero.



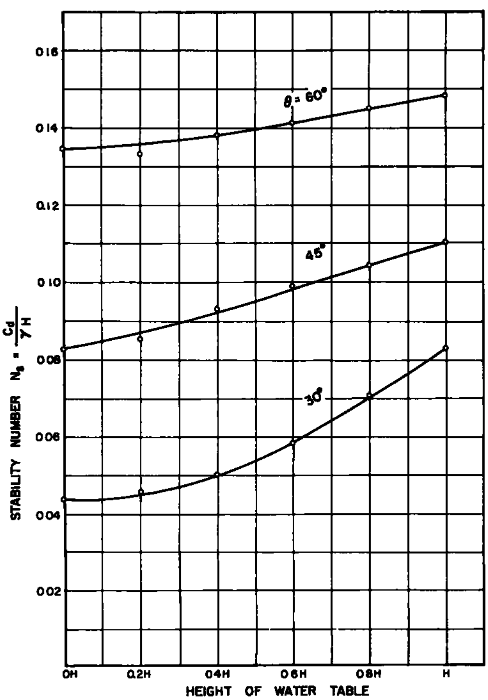
ϕ = 15°
h = 0.8H

Figure 12.



ϕ = 15°
h = 0.8H

Figure 13.



ϕ = 15°

Figure 14.

Curves are presented for three values of n_d the depth factor. The reader is referred to Figure 3 for the definition of n_d. Figures 7 and 9 show soils exhibiting internal friction. Curves for three values of $\lambda_{c\phi}$ are included on each.

$$\lambda_{c\phi} = \frac{\gamma H \tan \phi}{c}$$

in which ϕ = angle of internal friction,

On all curves the volume of excavation is found by:

$$V = n_A H^2$$

The dimensionless quantity n_A, the area factor, comes from the curves.

The depth of the bench for a particular value of N_s is found by interpolating between the lines marked n_h, the bench depth factor, also a dimensionless number.

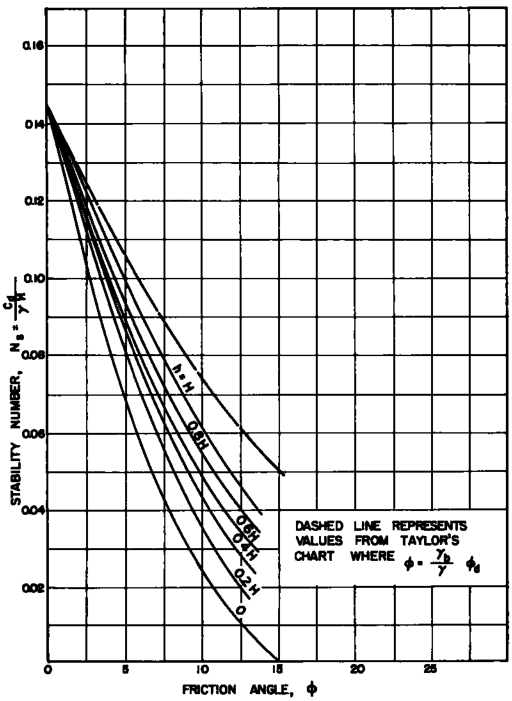
$$\text{Depth of bench} = n_h H$$

The bench width can now be found by

$$\text{Width of bench} = \frac{n_A}{n_h} H$$

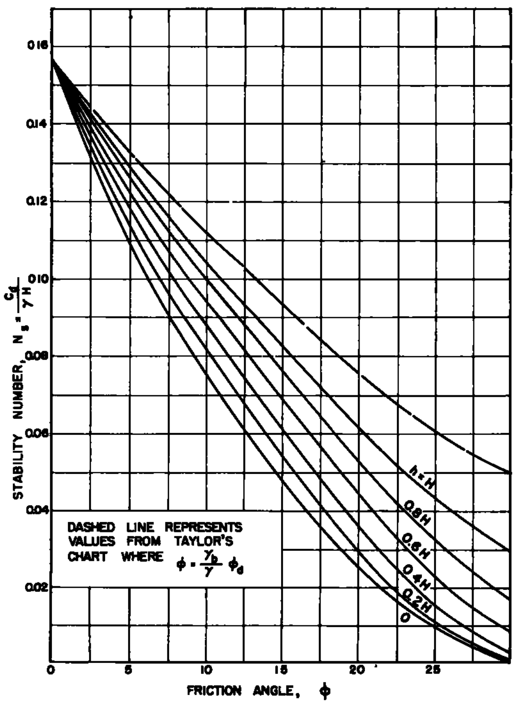
For the slope reduction curves, the reduced slope may be found by the use of n_A or

$$b = 2n_A + b_o$$



15° SLOPE

Figure 15.



30° SLOPE

Figure 16.

in which

b = reduced slope
n_A = area factor
b_o = original slope

Example Problem 1. A problem is presented in the determination of proper bench dimensions to increase the safety factor of a slope to 1.5.

Given: Initial slope, $b_o = 1$

$c = 600\ \text{lb/ft}^2$
$\phi = 22$ deg
$\gamma = 120\ \text{lb/ft}^3$
$H = 60$ ft

For these given conditions the evaluation of $\lambda_{c\phi}$ is

$$\lambda_{c\phi} = \frac{\gamma H \tan\phi}{c} = \frac{(120)(60)\tan 22\text{ deg}}{600} = 4.85$$

The stability number desired is

$$N_s = F_s \frac{\gamma H}{c} = 1.5\,\frac{(120)(60)}{600} = 18$$

By use of Figure 7, n_h and n_A can be determined by interpolation between $\lambda_{c\phi} = 4$ and $\lambda_{c\phi} = 6$.

$n_h = 0.38$
$n_A = 0.16$

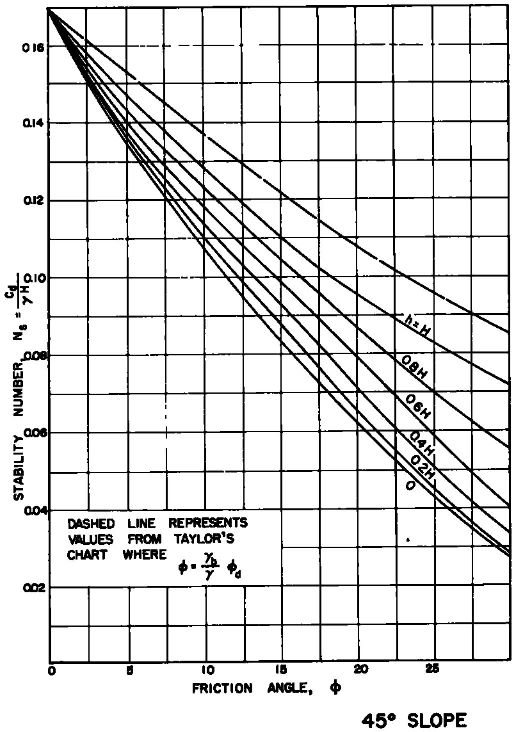


Figure 17.

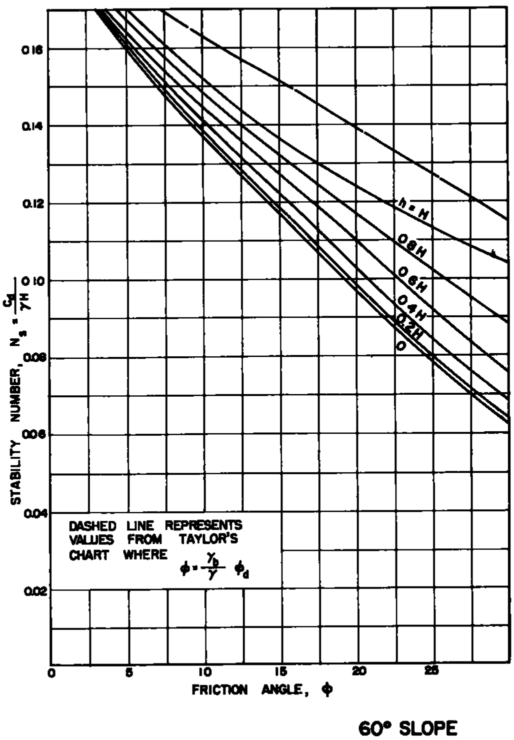


Figure 18.

Now the volume of excavation, depth, and width of the bench can be computed.

$$V = n_h H^2 = 0.16(60)^2 = 575 \text{ ft}^3\text{/lineal foot of slope}$$

$$\text{Depth of bench} = n_h H = 0.38(60) = 23 \text{ ft}$$

$$\text{Width of bench} = \frac{n_A}{n_h} H = \frac{0.16}{0.38}(60) = 25 \text{ ft}$$

Example Problem 2. In this problem the same given quantites found in problem 1 will be used but the factor of safety will be increased to 1.5 by reduction in slope angle.

Given: Initial slope, $b_o = 1$

$c = 600 \text{ lb/ft}^2$
$\phi = 22 \text{ deg}$
$\gamma = 120 \text{ lb/ft}^3$
$H = 60 \text{ ft}$

$\lambda_{c\phi}$ and N_s will also be the same as in problem 1.

$\lambda_{c\phi} = 4.85$
$N_s = 18$

Interpolating between the dashed lines for $\lambda_{c\phi}$ of 4 and 6 in Figure 7, n_A will be

$$n_A = 0.34$$

The volume of excavation and reduced slope are

$$v = n_A H^2 = 0.34(60)^2 = 1220 \text{ ft}^3\text{/lineal foot of slope}$$

$$b = 2n_A + b_o = 2(0.34) + 1 = 1.68$$

As seen in Figure 3, the slope crest must be moved back a distance $(b - b_o)H$. For this problem

$$(b - b_o)H = (1.68 - 1)\,60 = 41 \text{ ft}$$

From the results of these two problems it can be readily seen how much more effective benching is than slope reduction for increasing the safety of a slope against failure. Slope reduction requires more earth removal and a wider area of excavation at the slope crest. If slope unloading is being considered for controlling a landslide situation, the results of the curves presented here indicate that benching should be considered as a method for accomplishing the desired result.

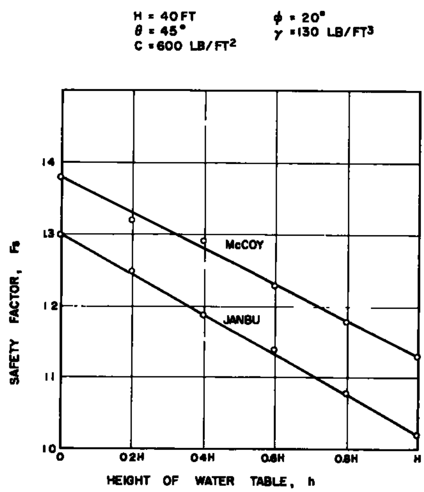


Figure 19.

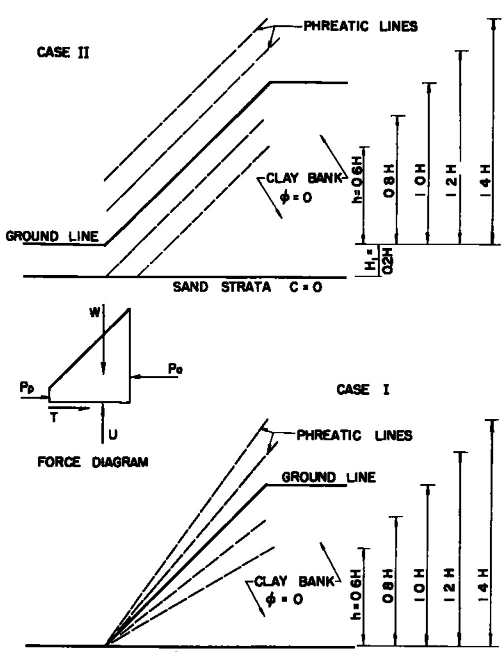


Figure 20.

Remedial Drainage

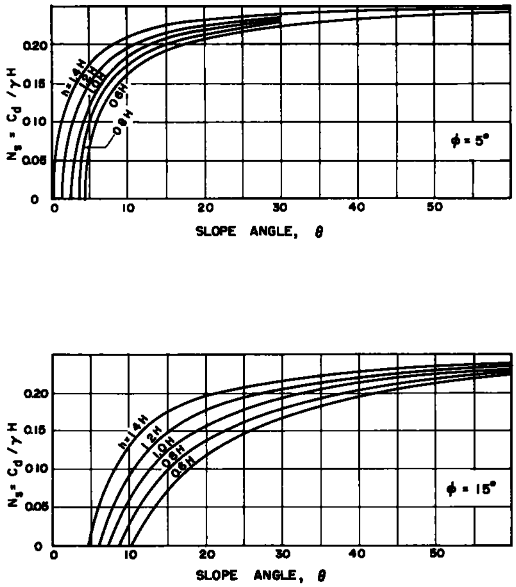
It is generally recognized by engineers that the installation of drainage works in an earth embankment or cut has as its purpose the relief of hydrostatic pressures rather than any substantial reduction in the water content of the soil. In this connection the term "water table" refers to that surface which is the locus of atmospheric pressure in the porewater, and not to any significant boundary between saturated and unsaturated soil. For twenty years engineers have had available procedures for determining the location of the water table subsequent to the installation of drainage, at least in idealized situations; and they have been able to compute the factor of safety corresponding to predetermined seepage patterns. Such analyses, however, have involved a laborious trial-and-error process for each drainage situation. The engineer has had little guidance in his preliminary appraisal of the over-all effects of any specific depression of the water table. The graphs presented herewith are intended to repair this deficiency.

Reduction of Porewater Pressure in Clay Banks

In order to present graphically with some quantitative values for a changing water table level, computations were made illustrating the effect of different water table levels upon several slopes with different soil strengths. The procedure used was taken from Taylor (2). Henceforth material from this reference will be labeled "Taylor's values."

The method of slope analysis employs the Swedish circle, solving for the forces graphically by the ϕ-circle method. As an illustration of the method used to obtain the curves, a slope of 45 deg with a friction angle of 15 deg was chosen and is shown in the figures. The solution is independent of height of the slope. Figure 11 shows the critical slip circle and lines of action of the weight of the soil mass and of the cohesion derived from Taylor's values. Figure 12 illustrates the method used in determining the resultant neutral force for the different water table levels.

The shape of the upper part of the flow net is one that will never be found in nature. However, it is felt that in order to standardize the flow nets for comparison and to avoid introducing other variables into the solution, the assumption shown is necessary. The top flow line is assumed to be tangent at the toe of the slope. This may also vary in natural conditions; however, the variation would be difficult to determine and unnecessarily complicate the solution. In any case, the error involved between computing the pressures used in this paper and actual pressures is very small and would not affect the values obtained for the stability numbers. Figure 13 shows the force diagram used in the computations of the stability numbers.



CASE I, $H_1 = 0$

Figure 21.

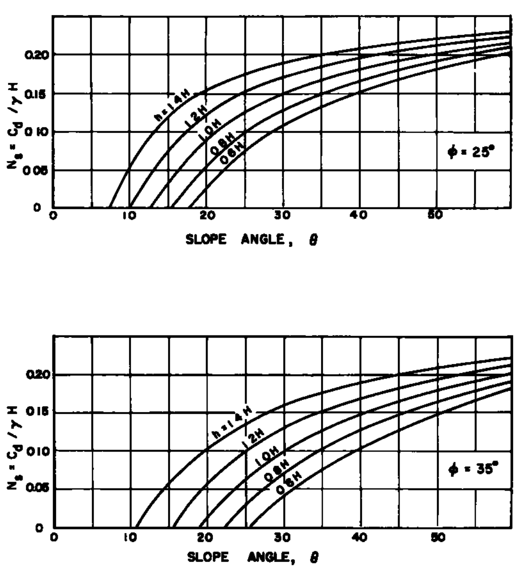
The stability numbers computed for the several slopes and friction angles were plotted against the water table heights and a smooth curve drawn through the points as shown in Figure 14. Values of the stability number for a water table height of 0. 2H were rather scattered in all curves because the graphical solution of the force diagram required the use of very small angles.

The results of the computations are shown in Figures 15 through 18. The curve for h= 0 is the curve shown on Taylor's charts for the zero boundary neutral force. The dashed curve represents values from Taylor's curves for sudden drawdown, while the intermediate curves give values for steady seepage with the water table level at the elevations shown.

The curves should prove useful in estimating the values of lowering the water table upon the stability of the slope by the use of a drainage plan. They may also be used to determine the maximum height of slope of a cut to be made where soil strengths and the water table levels are known or may be estimated.

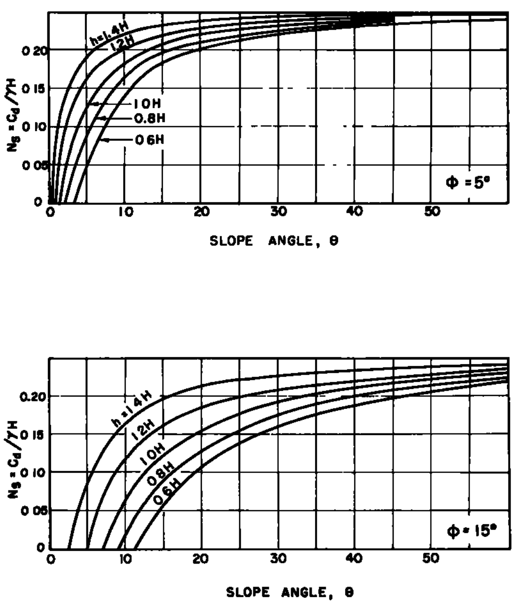
The curves presented assume that in every case the failure will occur as a toe circle, that is, the failure arc cuts the toe of the slope.

In a paper by Nilmar Janbu a straight line interpolation of the depth of the water table was used in working out an example (1). The same example was used here with the results shown in Figure 19.



CASE I, $H_1 = 0$

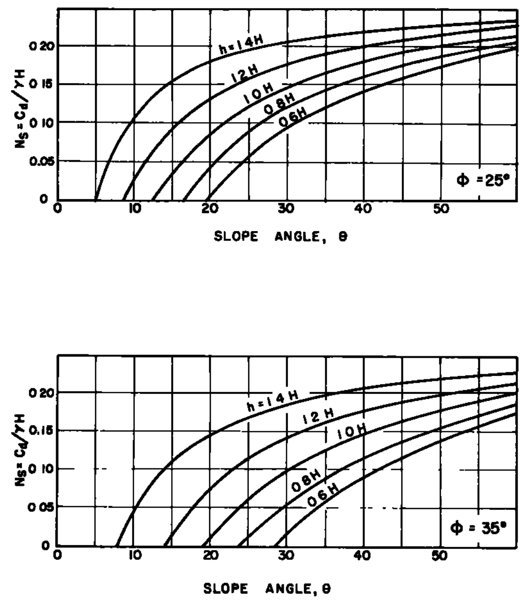
Figure 22.



CLAY BANK OVER SAND STRATUM

CASE II, $H_1 = 0.2H$

Figure 23.



CLAY BANK OVER SAND STRATUM

CASE II, $H_1 = 0.2H$

Figure 24.

Reduction of Water Pressure in an Underlying Aquifer

During rainy seasons an excess hydrostatic head may be built up in the underlying strata, threatening the stability of the slope. This force is resisted by the weight of the material above. As the hydrostatic pressure increases the shearing resistance of the pervious layer is reduced and when the active earth pressure at the crest becomes greater than the passive pressure at the toe of the slope plus the shearing resistance, the slope will fail. This failure takes place as the phenomenon of "sudden spreading." The clay slope fails and spreads very rapidly. The graphs presented here will enable one to relate the piezometric head in the pervious strata, the internal friction of the pervious strata, and the cohesion of the clay bank to a critical bank height. Thus, if the piezometric head in the sand strata is recorded periodically, a warning of impending danger can be given and action taken to forestall failure of the slope, or the effect of a drainage plan upon a slope that is sliding or in danger of sliding may be estimated.

Figure 20 shows the boundary conditions assumed for the solution of the graphs. The method used follows the suggestions given by Terzaghi and Peck for the analyses of sudden spreading of clay slopes (3). The phreatic lines were assumed to be straight and emerge at the toe of the slope where the sand strata was located at the toe of the slope. Where the pervious layer was deeper the phreatic line was assumed to be parallel to the ground surface. The sand strata was assumed to have no cohesion while the clay bank was assumed to have no internal friction. The curves showing values of the stability number vs slope angle for the different friction angles and water table heights are presented in Figures 21 to 24.

CONCLUSIONS

The preceding analyses confirm a general impression that engineering efforts to improve slope stability, whether by excavation or by drainage, are more apt to be successful with problems of instability in stiff soils (and steep slopes) than in soft soils (and flat slopes). The graphs presented in this paper should aid the engineer to decide in any ordinary instance whether excavation or drainage offers the more economical solution of this problem. If excavation, then it has been made clear in the preceding pages that benching requires less excavation than slope reduction in achieving a required factor of safety.

The value of lowering the water table increases when the slope has greater strength or internal friction. Therefore, in weaker slopes where trouble is likely to occur, lowering the water table will increase the safety of the slope by only a small amount. However, this small increase may assure the stability of the slope. It is difficult to make any general statement regarding the increased stability for all slopes upon lowering the water table as each slide will have different variables and conditions to be faced. However, in all cases the stability is increased, and the value of that increase may be estimated with the aid of the curves presented.

REFERENCES

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2. Taylor, D. W., "Fundamentals of Soil Mechanics." Chapter 16, John Wiley and Sons (1948).
3. Terzaghi and Peck, "Soil Mechanics in Engineering Practice." John Wiley and Sons (1948).

Appendix A

Derivation of Figure 6 and 8, $\phi = 0$

In general the curves for benched slopes are obtained by the solution of two problems. For a particular bench, as in Figure 4, the stability of the mass below the bench must be considered as well as the stability of the entire slope. This is shown by the two dashed critical circles. The curves in Figures 6 and 8 were found, then, by obtaining the factor of safety, F_s, for the small mass below the bench for a particular bench depth, $n_h H$. Then F_s for the entire slope was determined for this value of bench depth and several bench widths, $n_e H$. When F_s for the entire slope was found equal to F_s for the small earth mass, this determined the widest bench that could economically be cut for that particular bench depth and constitutes a point on the curve of N_s versus n_A.

Example Problem A-1. This problem illustrates the above discussion by showing the procedure used in obtaining a point on the bench curve for $n_d = 2$, Figure 6.

Given: $b_o = 1$ $\quad \phi = 1$
$n_d = 2$ $\quad c = 800\ \text{lb/ft}^2$
$\quad \gamma = 120\ \text{lb/ft}^3$
$n_h = 0.1$
$H = 30$ ft

The F_s for the small earth mass is obtained by determining N_s from Janbu's curve in Figure 2-1 (1). This figure is similar to the curves presented by Terzaghi and Peck.

$$F_s = N_s \frac{c}{\gamma J} = 5.64 \frac{800}{(120)(27)} = 1.39$$

The x and y coordinates for the critical circle of the small mass below the bench is obtained from other curves of the same plot. The intersection of the critical circle and the bench line determines the width of the first trial bench in this example for the first trial

$$n_e = 2.05$$

For this bench width F_s for the entire slope was obtained by following the procedure outlined by Janbu (1). Benching is taken care of by considering the earth removed as constituting an upward force on the slope.

$$F_s = 6.2 \frac{800}{(120)(30)} = 1.38, \text{ for } n_e = 2.05$$

Since F_s for the entire slope is slightly smaller than F_s for the small mass, a wider bench may be cut necessitating another trial n_e. If F_s for the entire slope had been larger for this first trial, the F_s for the smaller mass would be used for a point on the final curves. This condition occurs for small values of n_h and determines the first part of the final curves which is concave upward.

For a second trial let $n_e = 2.4$. Using the same procedure as above

$$F_s = 6.4 \frac{800}{(120)(30)} = 1.42, \text{ for } n_e = 2.4$$

Now F_s for the entire slope is larger than F_s for the small mass below the bench. To find the bench width where both are the same, all trial values are plotted as in Figure 10. The volume of the material removed per lineal foot of slope is

$$V = n_e n_h H^2$$

$$\text{Let } n_A = n_e n_h = (2.05)(0.1) = 0.205$$

$$V = n_A H^2 = 0.205H^2$$

Point A then represents the widest bench which should be excavated for a bench depth of $n_h = 0.1$.

The entire bench curve for $n_d = 2.0$ is determined by the method outlined above with n_h being taken from 0.1 to 0.5 at 0.1 intervals. For the final curve F_s was converted to N_s.

Example Problem A-2. The dashed lines on Figures 6 and 8 represent an increase in N_s for slope reduction and were obtained by the following method. Referring to Figure 8, a slope less than b_o was considered, such as b = 1.5. The N_s value (5.75) for this slope was obtained from Figure 2-1. The volume of excavation per lineal foot of slope was found by

$$V = \frac{(b - b_o)}{2} H^2$$

Here a quantity is multiplied by H^2, as in the case for a benched slope. Therefore, to plot this curve along with the bench curve

$$n_A = \frac{b - b_o}{2} = \frac{1.5 - 1}{2} = 0.25$$

The volume excavated would then be

$$V = n_A H^2 = 0.25H^2$$

This allows comparison of volumes of excavation for benching and slope reduction for the same value of N_s. The entire slope reduction curve was obtained by increasing b by intervals of 0.25.

Appendix B

Derivation of Figures 7 and 9, $\phi > 0$

These curves were derived similarly to those on Figures 6 and 8 in that F_s for the entire slope was compared to F_s for the small earth mass below the bench for a certain value of bench depth.

Example Problem B-1. Consider the determination of a point on the bench curve of Figure 7 for $\lambda_{c\phi} = 4.0$.

Given: $b_o = 1$ $\quad \phi = 20$ deg
$n_h = 0.4$ $\quad c = 419$ lb/ft^2
$H = 40$ ft $\quad \gamma = 115$ lb/ft^3

F_s for the small earth mass is obtained from Janbu's curve in Figure 6 (1).

The x and y coordinates for the critical circle of the small earth mass are also obtained from that figure. The intersection of this circle and the bench line determined the initial bench width of $n_e = 0.3$.

F_s for the entire slope for a particular value of n_e must be accomplished by first finding the approximate location of the critical circle for failure of the entire slope. Then F_s is determined by the us of the ϕ-circle method. Locating the critical circle will be discussed first.

It was felt that the critical circle for a benched slope of a given slope angle would fall near the critical circle of a slope which had been reduced somewhat below the given slope angle, or a reduced slope would exist that had essentially the same driving moments due to the soil mass as the benched slope. At least if this condition was met the critical circle should give a reasonable value for F_s since minor changes of the critical circle do not change F_s appreciably.

Consequently F_s was determined for the critical circles of several reduced slopes until a minimum F_s for the benched slope was found. Usually the slope was reduced 2 deg between each trial.

In the current example the three trial critical circles used for $n_e = 0.3$ were for reduced slopes of 38 deg, 36 deg, and 34 deg. It was found that F_s for a reduced slope of 36 deg was the smallest and is bracketed by two higher values. Therefore this value of F_s was selected for $n_e = 0.3$.

Figure 10 shows the graphical procedure used in finding F_s by the ϕ-circle method. The resultant weight vector, W, was located by taking moments about the toe of the slope. From the intersection of W and the line of action of C, the total cohesive force acting along the critical circle, lines were drawn tangent to three different ϕ-circles. C is then evaluated for the three cases.

The factors of safety with respect to c and ϕ for the three values of ϕ, were determined by

$$F_c = \frac{c\ \text{(effective)}}{c\ \text{(required)}}$$

$$F_\phi = \frac{\tan\phi\ \text{(effective)}}{\tan\phi\ \text{(required)}}$$

F_s was then found from the small graph, Figure 11, such that

$$F_s = F_c = F_\phi$$

$$F_s = 1.36, \text{ for } n_e = 0.3$$

Since this value is smaller than F_s for the small earth mass, the bench may be widened. The second width trial value is $n_e = 0.4$. This time the same critical centers were used and the minimum F_s is

$$F_s = 1.45, \text{ for } n_e = 0.4$$

Still smaller, a third trial bench width of n = 0.5 was computed in a similar manner.

$$F_s = 1.53, \text{ for } n_e = 0.5$$

Again, as in Appendix A, all trial values are plotted (see Fig. 10) and a point on the final curve is obtained. Points were figured for values of n_h from 0.1 to 0.5 at 0.1 intervals.

The curves for reduced slope on Figures 7 and 9 were found by the same method outlined in Appendix A except that N_s values came from Janbu's Figure 6.