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STABILITY OF EARTH SLOPES

BY DONALD W. TAYLOR, MEMBER *

SYNOPSIS

THIS paper presents a review of several methods which have been proposed for analyzing the stability of earth slopes, with comparisons of the results they furnish. Two methods which appear to give consistent and reliable results have been studied in considerable detail, and complete mathematical solutions have been obtained. Although the equations of the mathematical solutions are somewhat involved, they have been evaluated, tabulated and plotted in such form that the solution to a practical problem may be found almost at a glance.

Numerous simplifying assumptions must be made in any approach to this problem, an important one being homogeneity of the soil. Consequently it must be recognized that in general no solution can be accepted as wholly reliable. However, as indications of the conditions which exist, and as aids to judgment, the results may often be of great value to the engineer, and they are presented herein with that end in view.

Measurement of the constants which describe the shearing strength of the soil is briefly discussed. As understanding of the phenomena of shear in soils becomes more advanced, the reliability of results of stability computations will increase and better methods of computation may be developed. At present, the accuracy with which shearing strength may be determined is decidedly the limiting feature, and it is

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probable that the methods recommended herein will prove adequate for some time to come.

Values for unit weight and their applicability are discussed. The effect of seeping water is analyzed, and a procedure is recommended which does not require determination of a flow net.

General Considerations and Assumptions

There are three distinct parts to an analysis of the stability of a slope.

1. *The Testing of Samples to determine the Cohesion and Angle of Internal Friction.* — If the analysis is for a natural slope it is essential that the samples be undisturbed. In such important respects as rate of shear application and state of initial consolidation, the conditions of testing must represent as closely as possible the most unfavorable conditions ever likely to occur in the actual slope.

2. *The Study of Items which are Known to Enter but which Cannot be Accounted for in the Computations.* — The most important of such items is the progressive cracking which will start at the top of the slope where the soil is in tension, and, aided by water pressure and perhaps frost action, may progress to considerable depth. In addition, there are the effects of the non-homogeneous nature of the typical soil and other variations from the ideal conditions which must be assumed. Decisions on these complicated points will tax the judgment of the most competent and experienced of engineers to the limit, and for important projects, where stability is essential, the best in consultation advice is to be recommended. For preliminary studies, however, conservative decisions on such points will lead to analyses which will at least give valuable indications of the condition of stability.

3. *The Computations Themselves.* — Parts 1 and 2 are both of fully as much importance as part 3. The principal aim of the main body of this paper, however, is to present a practical and simple method of handling part 3. Part 1 will be covered only in a general way, while phases of part 2 are discussed near the end of the paper.

If a slope such as that illustrated in Fig. 1 (*a*) is to fail, all shearing strength must be overcome along some surface, which then becomes a surface of rupture. The arc *AB* in this figure represents one of an infinite number of possible traces on which the failure might occur. For the simple case which is to be considered here the slope is assumed constant, the top surface level, and the soil homogeneous throughout.

Thus a simplified section is taken, but it may be noted that many actual slopes may be closely approximated by such an ideal section.

It is assumed that the problem is two-dimensional, which theoretically requires infinite running length of slope. However, if the cross section investigated holds for a running length of roughly two or more times the trace of the rupture, it is probable that the two-dimensional case holds within required accuracy.

Most methods of approach to the problem assume that the rupture surface passes through the toe of the slope, point A of Fig. 1 (a). It is known that the higher the slope the more likelihood of failure, thus, so long as the material is homogeneous to an unlimited depth, a rupture surface passing through a point part way up the slope is not to be expected. However, the possibility that the rupture surface may pass below the toe of the slope and break out at the surface some distance away must not be overlooked.

The determination of the shape and location of the surface of rupture is a very important consideration. If stability analyses could be made for each of the infinite number of possible surfaces, that one showing the most unfavorable condition of stability would be the rupture surface in case of failure. As such a procedure is at present impossible, the surface of rupture is determined in the various methods of solution (a) by pure assumption, (b) by mathematical analysis, or (c) by assumptions based on studies of actual slides. This point will be discussed later for the individual methods. In plastic soils, instead of a definite surface of rupture a zone of plastic flow may be expected. This need cause no concern here, however, since if a slope of such a material is just at the point of failure, the use of any surface composed of slip lines within the plastic zone as a rupture surface should show a limiting condition of equilibrium.

The shearing strength of the soil is assumed to follow the empirical relationship known as Coulomb's Law —

$$s = c + n \tan \phi$$

wherein s is the unit shearing strength, c the unit no-load shearing strength or unit cohesion, n the applied normal stress on the surface of rupture, and ϕ the effective angle of internal friction. It must be carefully noted that the values for cohesion and effective angle of internal friction are not necessarily constants for a given soil, but are intended to represent quantities which may be depended upon to hold for a definite set of conditions. Any attempt at a thorough discussion of the subject of shearing strength of cohesive soils is far beyond the scope of this paper. However, brief mention of a few of the most salient points may be desirable.

The linear relation expressed by Coulomb's Law must be looked upon as an approximation. If a series of laboratory tests is run, conforming to a given set of conditions, a plot of shearing strength against normal pressure will usually show a definite curvature. Generally, however, this curve may be approximated by a straight line without introducing serious error.

Foremost among the conditions in nature which must be reproduced in the laboratory are the rate of application of shearing strain and the state of initial consolidation. Terzaghi has discussed these items briefly (Fig. 9, reference 9*a*),* and they have been a subject of study by many investigators. In Sweden, where the principles of the method which is used herein originated, it has been found that for many cases actual conditions are best represented by an effective angle of internal friction of zero. In general, however, it would not be advisable to make this assumption without investigation.

Another item of great importance is the loss in shearing strength which many clays show when subjected to large shearing strain. The stress-strain curves for such clays show the stress rising with increasing strain to a maximum value, after which it decreases and approaches an ultimate value which may be much less than the maximum. Since a rupture surface tends to develop progressively rather than with all the points at the same state of strain, it is generally the ultimate value that should be used for the shearing strength rather than the maximum value.

In recent years much progress has been made in the development of a satisfactory understanding of the behavior of cohesive soils in shear, but many features are still only partially understood. It is probable that there are constant values for effective cohesion and effective angle of internal friction for Coulomb's Equation which approximately but adequately express the shearing strength for any given set of conditions. Undoubtedly the soil engineer of the future will be able to furnish better values for these constants, and quite possibly he may develop better methods for using them in stability analyses. However, the limiting factor of such analyses is the determination of the shearing strength which a soil possesses. Thus the methods presented herein appear to be adequate, and with the development of more accurate methods for determining values for shearing strength may be used in the future with increasing dependability.

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* Numbers in parentheses refer to Bibliography at end of paper.

The subject of undisturbed sampling should not be passed without mention. If the structure of a soil is disturbed in sampling, the shearing strength is changed, and, regardless of how accurately other conditions are reproduced in the testing, this discrepancy is always present. When an analysis is made for a slope of a natural clay which has a structure such that disturbance causes radical change of properties, it is impossible to overemphasize the importance of requiring samples which are as nearly undisturbed as can be obtained.

The scope of the methods discussed herein is limited to clays or other cohesive materials which are not fissured. Considerations of stiff fissured clays, where the point in question is that of preventing disintegration rather than one of stability, have been discussed by Terzaghi (9*b*).

Summary of Methods

A number of methods for stability computations have been advanced. All assume homogeneous soil, constant angle of slope, level top surface and shearing strength as expressed by Coulomb's Equation. Unless otherwise noted, the assumptions are also made that cohesion is constant along the entire rupture surface and the rupture surface passes through the toe of the slope. The commonest methods may be summarized as follows:

1. The *Culmann Method* (1) assumes rupture will occur on a plane. It is of interest only as a classical solution, since actual failure surfaces are invariably curved. The general formula for this method is given later under Comparisons of Methods.

2. The *Résal-Frontard Method* (2, 3) assumes the soil mass to act as a slope of infinite extent, and, by use of conjugate stress relationships, results in an equation for the rupture surface. This method has been criticized because the results indicate that the mass above the rupture surface is not in static equilibrium when just at the point of failure with all shearing strength being utilized. However, the results are on the side of safety, and it is interesting to note that on one very important point they agree with actual conditions by indicating that the upper part of the mass is in tension. This method assumes that no cohesion may be depended upon within the depth to which tension occurs. Formulæ are given later under Comparisons of Methods.

3. The *Circular Arc Method* was first proposed by K. E. Petterson, based on his study of the failure of a quay wall in Goeteborg in 1915 or 1916. The justification that circular arcs are close approximations of actual rupture surfaces comes from field investigations of a large num-

ber of actual slides, especially in railroad cuts, by the Swedish Geotechnical Commission (4). An infinite number of arcs may be drawn for any given slope, the one to be used being that one which is least stable. That such arcs may either pass through the toe of the slope or may pass below this point is borne out by the field investigations; thus the method is not limited to arcs through the toe of the slope. This method has been widely accepted as satisfactory, and several methods of procedure based on the circular arc have been proposed, among which are the following:

3 (*a*). *Method of Slices* (4, 5, 6). — This method was advanced by the Swedish Geotechnical Commission and developed in quite some detail by Professor W. Fellenius. By dividing the mass above the rupture plane into vertical slices and assuming the forces on opposite sides of each slice are equal and opposite, a statically determinate problem is obtained, and semigraphical methods have been devised by which the stability of the mass may be analyzed for any given circle. The main objection to this or any other graphical method rests in the fact that the most dangerous one of an infinite number of possible circles must be found, and thus the graphical procedure must be repeated for a large number of circles. It is to be noted that some assumption must be introduced to make the problem statically determinate; the one mentioned above, which is but one of several which have been proposed, is generally recognized as the most suitable.

The work of Professor Fellenius includes a general solution which is the result of many series of graphical analyses based on this method, and which is presented (5) in the form of nests of curves. For the special case of $\phi = 0$ he also obtained a general mathematical solution. In addition he has given data on locations of critical circles which will be discussed later.

3 (*b*). *ϕ-Circle Method.* — This is one of the two methods upon which the general solution given in this paper is based. An assumption is introduced which may be more easily justified than that of method 3 (*a*), and the mathematical solution which has been derived eliminates all graphical work. A more complete description will be given later.

3 (*c*). *The Jáky Method* (9*c*) is a mathematical solution based on the equation of continuity of stress. The boundary conditions which locate the critical circle place too much dependence on the circular assumption and lead to results which are somewhat on the unsafe side, as discussed later.

4. *The Spiral Method* (7) assumes the rupture surface to be a logarithmic spiral. No further assumption is required to make the problem statically determinate, which constitutes the important advantage of this method. On the other hand, solutions based on spiral surfaces are not as easily handled by graphics or mathematics as are those based on circular arcs. As in the circular arc method, all possible logarithmic spirals, passing either through or below the toe of the slope, should be investigated to locate which is most dangerous. A mathematical solution for this method has been obtained by the writer and is covered in detail later.

The ϕ-Circle Method

The solution of the slope stability problem is developed below, using the ϕ-Circle Method. The basic assumption which characterizes this method is explained following the description of the forces which enter.

The ϕ-Circle Method was proposed some years ago by Professors Glennon Gilboy and Arthur Casagrande, its initial use being in the development of a completely graphical solution of the slope problem. For any circle that is analyzed, the result by this solution is a vector, the length of which represents the quantity $\frac{2c_1}{w}$, wherein w is the unit weight of the soil and c_1 is the unit cohesion required for equilibrium. It became evident, from the graphical layout for any given inclination of slope and any given angle of internal friction, that one plot could represent the case for various heights of slope merely by the use of different scales. Hence, if the length of the vector is divided by any characteristic linear dimension, such as H, the vertical height of the slope, the result is an abstract number $\frac{2c_1}{wH}$. This number, when determined for the most dangerous circle, describes the requirements for stability of any case involving the given slope and angle of internal friction. This relationship suggested the possibility of obtaining a general solution for all slopes and all angles of internal friction so that, once determined, there would be no further need of analyzing each individual case. Some years earlier Fellenius had originated the expression which in the notation of this paper is $\frac{4c_1}{wH}$, but in his paper (5) he did not emphasize the basic nature of this relationship.

In the mathematical solutions which have since been set up by the writer, the form used for this abstract number is $\frac{c}{FwH}$, wherein F is the factor of safety with respect to cohesion, and c is the actual unit cohesion for the soil in question. This basic dimensionless expression will be called the "Stability Number."

Two different factors of safety have been proposed for use in stability problems. Fellenius and most other investigators have used the ratio of actual shearing strength to critical shearing strength, which is in agreement with the usual conception of factor of safety, and will be called the true factor of safety. The other factor has been used by Jáky (9*c*) and Rendulic (7), and may be described as the ratio between actual cohesion and critical cohesion. Of the two items which comprise the shearing strength, namely, cohesion and friction, this latter factor has

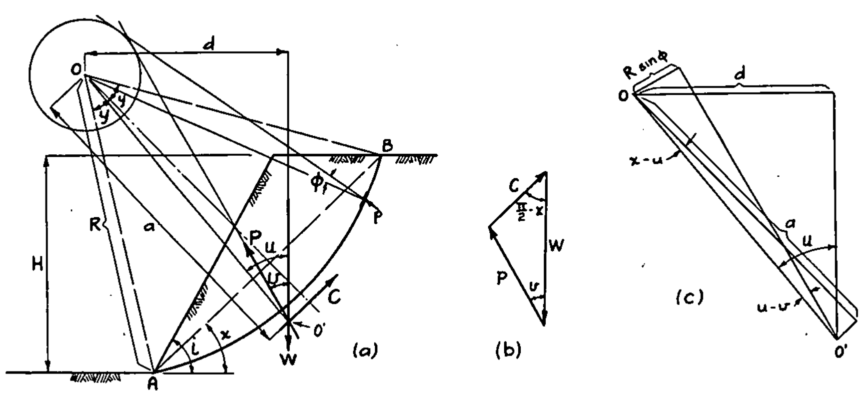


FIG. 1.—SKETCHES SHOWING ELEMENTS OF THE ϕ-CIRCLE METHOD FOR CIRCLES PASSING THROUGH TOE OF SLOPE

bearing on the cohesion only, and will be called herein the factor of safety with respect to cohesion. In setting up mathematical solutions, the use of this latter factor proves to be simpler, thus it is used in the derivations given herein. However, it will be shown later that the true factor of safety may easily be adapted in the results of these solutions.

In Fig. 1 (*a*), AB is any circular arc through A, the position of the center O being described by the two variable co-ordinate angles x and y. Arcs which pass below the toe of the slope will be treated later. The section considered extends a unit distance in the third dimension. The forces acting on the mass above the arc are shown in Fig. 1 (*a*), while Fig. 1 (*b*) shows the equilibrium polygon. The three forces entering are—

W, the Weight of the Mass. — The vector representing W will act vertically through the center of gravity of the mass, and its magnitude and line of action may be found easily by any one of several methods.

C, the Resultant Cohesion. — Its magnitude is $c_1\bar{L}$, where c_1 is the unit cohesion required for equilibrium and $\bar{L}$ is the length of the chord AB. Its line of action is parallel to the chord AB, and its moment arm, a, is described by —

$$c_1\bar{L}a = c_1\widehat{L}R \quad \text{or} \quad a = \frac{R\widehat{L}}{\bar{L}}$$

where $\widehat{L}$ is the length of arc AB. Thus the line of action of C may be found, and its position is independent of the magnitude of the cohesion.

P, the Resultant Force transmitted from Grain to Grain of the Soil across the Arc AB. — The intersection of W and C is known. Since the three forces W, C and P must be concurrent, P must also pass through this intersection. With W known in magnitude and direction and the direction of C also known, the force polygon may be constructed if a second point can be obtained on P to determine its direction. This is accomplished by the basic assumption of the ϕ-Circle Method.

P is made up of small elementary forces, such as p, which must act at an obliquity of ϕ to the arc AB. If p is produced and a small circle is drawn with center at O tangent to the produced line, it will be seen that the p force for any other element of the arc AB will also be tangent to it. This small circle is called the ϕ-circle. Any two such p forces will intersect just outside of the ϕ-circle so their resultant would pass just outside this circle, and by the same reasoning P must pass outside. The assumption introduced is that P is tangent to the ϕ-circle. It is to be noted that this idea is not new, being only a new application of a scheme developed by Dr. H. Krey (8) and used by him in other types of analyses. Studies have been made to estimate the degree of inaccuracy involved by this assumption, and a discussion of these will be introduced later.

The mathematical solution is given, first for the case of circles passing through the toe of the slope, and followed by the case of circles passing below the toe of the slope.

From Fig. 1 (a):

$$C = c_1\bar{L} = \frac{c\bar{L}}{F} = \frac{2}{F}cR \sin y \tag{1}$$

$$W = wR^2y - wR^2 \sin y \cos y + \frac{wH^2}{2} (\cot x - \cot i) \tag{2}$$

$$R=\frac{H}{2} \csc x \csc y \tag{3}$$

$$\begin{aligned}Wd=[wR^2y]\left[\frac{2R}{3}\,\frac{\sin y}{y}\sin x\right]-[wR^2 \sin y \cos y]\left[\frac{2R}{3} \cos y \sin x\right] \\ +\left[\frac{wH^2}{2} \cot x\right]\left[\frac{H}{3} \cot x+R \sin (x-y)\right] \\ -\left[\frac{wH^2}{2} \cot i\right]\left[\frac{H}{3} \cot i+R \sin (x-y)\right]\end{aligned}$$

which, reduced and combined with (3), gives —

$$Wd=\frac{wH^3}{12}\left[1-2 \cot^2 i+3 \cot i \cot x-3 \cot i \cot y+3 \cot x \cot y\right] \tag{4}$$

From Fig. 1 (c):

$$OO'=d \csc u \tag{5}$$
$$OO'=a \sec (x-u)=R\, y \csc y \sec (x-u) \tag{6}$$
$$OO'=R \sin \phi \csc (u-v) \tag{7}$$

From Fig. 1 (b):

$$\frac{W}{C}=\frac{\cos (x-v)}{\sin v}=\cos x \cot v+\sin x \tag{8}$$

substituting (3) in (2) and the result in (4)

$$\frac{H}{2d}=\frac{\frac{1}{2} \csc^2 x\,(y \csc^2 y-\cot y)+\cot x-\cot i}{\frac{1}{3}\,(1-\cot^2 i)+\cot i\,(\cot x-\cot y)+\cot x \cot y} \tag{9}$$

From (5), (6) and (3):

$$\cot u=\frac{H}{2d}\, y \sec x \csc x \csc^2 y-\tan x \tag{10}$$

From (5), (7) and (3):

$$\sin (u-v)=\frac{H}{2d} \sin u \csc x \csc y \sin \phi \tag{11}$$

placing (3) in (1) and (2), then setting (8) equal to the ratio of (2) and (1)

$$\frac{c}{FwH}=\frac{\frac{1}{2} \csc^2 x\,(y \csc^2 y-\cot y)+\cot x-\cot i}{2 \cot x \cot v+2} \tag{12}$$

The solution for the case where the rupture surface passes below the toe of the slope is almost as simple as that for the above case. The only important difference is that another variable enters which is designated by n, and is shown in Fig. 2 (a). However, there are still only two degrees of freedom, since a condition enters which must be satisfied.

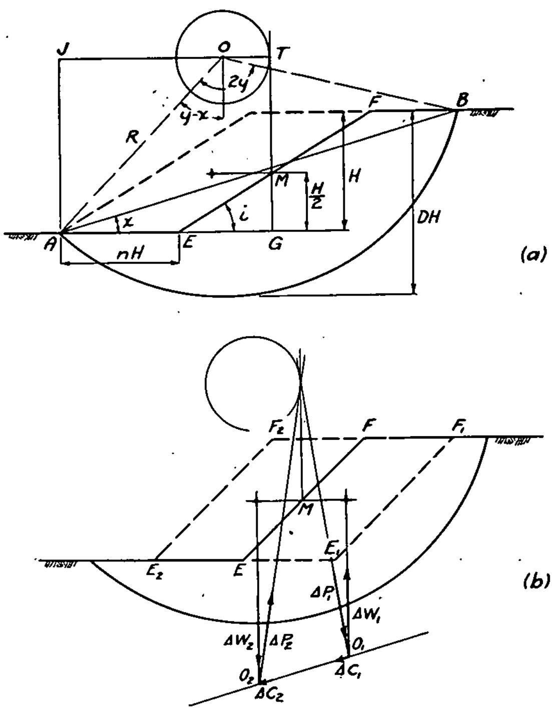


FIG. 2. — SKETCHES SHOWING ELEMENTS OF THE ϕ-CIRCLE METHOD FOR CIRCLES PASSING BELOW TOE OF SLOPE

Consider the case shown in Fig. 2 (b) where the right vertical tangent of the ϕ-circle passes through the mid-point of the slope M. If the slope EF is cut away parallel to itself to the line E_1F_1, the changes in forces W, C and P may be studied by a ϕ-circle analysis. Since W is decreased, its change ΔW_1 is an upward force which will act through the center of gravity of the area removed. The line of action of C must be the same before and after the change, thus ΔW_1 and ΔC_1 intersect at point O_1, and ΔP_1 must pass through this point and also be tangent to the ϕ-circle. ΔC_1 acts to the left, which indicates a decrease in the required cohesion, and it is seen that the removal of the mass EFF_1E_1 has given a more stable condition.

Similarly, if the slope EF is built up to E_2F_2, adding force ΔW_2, the analysis demonstrates that ΔC_2 also acts to the left. Therefore moving the mid-point of the slope to either side of the right vertical tangent of the ϕ-circle leads to greater stability, and the requirement that the mid-point must be on this tangent for the most dangerous circle must be introduced.

It may also be seen that there is little need of investigating cases of rupture arcs passing through the toe of the slope for which the mid-point of the slope is to the left of the right vertical ϕ-circle tangent, since a more dangerous case is obtained by moving the same circle to the left, allowing it to pass below the toe of the slope.

The condition may be obtained from Fig. 2 (a), as follows:

$$\overline{AE}+\overline{EG}=\overline{JO}+\overline{OT}$$

or

$$nH+\tfrac{1}{2}\,H\cot i=R\sin(y-x)+R\sin\phi$$

and inserting R from equation (3)

$$n=\tfrac{1}{2}\,(\cot x-\cot y-\cot i+\sin\phi\csc x\csc y) \tag{13}$$

This equation could be used to eliminate n from the equations which follow. However, the requirement that n be positive must always be checked, and it is convenient to retain n as a dependent variable.

As compared to the case where the rupture arc passes through the toe of the slope, shown dotted in Fig. 2 (a), the change in W is —

$$-wnH^2=\frac{wH^2}{2}\,(-2n)$$

the change in Wd is —

$$(-wnH^2)\,(R\sin\phi-\tfrac{1}{2}\,nH)=\frac{wH^3}{4}\,(2n^2-2n\sin\phi\csc x\csc y)$$

If these changes are inserted in equations (9) to (12), inclusive, there results —

$$\frac{H}{2d}=\frac{\tfrac{1}{2}\csc^2 x\,(y\csc^2 y-\cot y)+\cot x-\cot i-2n}{\tfrac{1}{3}\,(1-2\cot^2 i)+\cot i\,(\cot x-\cot y)+\cot x\cot y+2n^2-2n\sin\phi\csc x\cdot\csc y} \tag{14}$$

$$\cot u = \frac{H}{2d} y \sec x \csc x \csc^2 y - \tan x \tag{15}$$

$$\sin (u-v) = \frac{H}{2d} \sin u \csc x \csc y \sin \phi \tag{16}$$

$$\frac{c}{FwH} = \frac{\frac{1}{2} \csc^2 x \, (y \csc^2 y - \cot y) + \cot x - \cot i - 2n}{2 \cot x \cot v + 2} \tag{17}$$

To obtain the value of $\frac{c}{FwH}$ for any desired values of slope and friction angles and any chosen values of x and y, equation (13) may be tried first to determine whether or not the circle will pass through the toe of the slope. As a negative value of n is impossible, equation (13) must be discarded if it shows a negative result, and the circle will pass through the toe. For this case, evaluation of equations (9) to (12), inclusive, used in numerical order, give in succession $\frac{H}{2d}$, u, v and finally $\frac{c}{FwH}$. If equation (13) shows a positive value of n, the procedure is the same; equations (9) to (12) may be used for circles through the toe, while for circles below the toe equations (14) to (17) are to be used.

For the case of $\phi = 0$ the above equations may be simplified, and by differentiation with respect to the variable angles x and y the location of the critical circle may be obtained. The results for this special case will be discussed later. For the general case, where the friction angle is greater than zero, the very tedious method of trial must be resorted to, but the use of computing machines is of great assistance.

The procedure used in determining the tabulations was to choose values for x and y and compute $\frac{c}{FwH}$ as outlined. The center of the circle corresponding to these co-ordinates was plotted and at this point the value of $\frac{c}{FwH}$ recorded. Several such centers were tried, each helping to choose the following one until enough values were obtained to allow contouring and the determination of the maximum or critical value of $\frac{c}{FwH}$. After the procedure was standardized it was found that for each case of slope and friction angle from 10 to 20 trial centers were needed to locate the maximum. This procedure was carried out for a representative group of values of friction and slope angles, and Table I gives all pertinent data for all cases that were computed.

TABLE I

DATA ON CRITICAL CIRCLES BY ϕ-CIRCLE METHOD

i	ϕ	x	y	n	D	$\frac{c}{FwH}$	Corrected $\frac{c}{FwH}$*
90 . . .	0	47.6	15.1	–	–	.261	.261
	5	50	14	–	–	.239	.239
	10	53	13.5	–	–	.218	.218
	15	56	13	–	–	.199	.199
	20	58	12	–	–	.182	.182
	25	60	11	–	–	.166	.166
75 . . .	0	41.8	25.9	–	–	.219	.219
	5	45	25	–	–	.195	.195
	10	47.5	23.5	–	–	.173	.173
	15	50	23	–	–	.153	.152
	20	53	22	–	–	.135	.134
	25	56	22	–	–	.118	.117
60 . . .	0	35.3	35.4	–	–	.191	.191
	5	38.5	34.5	–	–	.163	.162
	10	41	33	–	–	.139	.138
	15	44	31.5	–	–	.118	.116
	20	46.5	30.2	–	–	.098	.097
	25	50	30	–	–	.081	.079
45 . . .	0	(28.2)†	(44.7)	–	(1.062)	(.170)	(.170)
	5	31.2	42.1	–	1.026	.138	.136
	10	34	39.7	–	1.006	.110	.108
	15	36.1	37.2	–	1.001	.086	.083
	20	38	34.5	–	–	.065	.062
	25	40	31	–	–	.046	.044
30 . . .	0	(20)	(53.4)	–	(1.301)	(.156)	(.156)
	5	(23)	(48)	–	(1.161)	(.112)	(.110)
		20	53	0.29	1.332	.113	.110
	10	25	44	–	1.092	.078	.075
	15	27	39	–	1.038	.049	.046
	20	28	31	–	1.003	.027	.025
	25	29	25	–	–	.010	.009
15 . . .	0	(10.6)	(60.7)	–	(2.117)	(.145)	(.145)
	5	(12.5)	(47)	–	(1.549)	(.072)	(.068)
		11	47.5	0.55	1.697	.074	.070
	10	(14)	(34)	–	(1.222)	(.024)	(.023)
		14	34	0.04	1.222	.024	.023
All values‡ .	0	0	66.8	∞	∞	.181	.181

* With ϕ-circle correction applied.

† Figures in parentheses are values for most dangerous circle through the toe when a more dangerous circle exists which passes below the toe.

‡ A critical value at infinite depth. (See Fig. 8.)

As may be noted from this table, the critical circle through the toe of the slope was determined for each case. For cases of ϕ greater than zero in only three instances did the most dangerous circle pass below the toe, and for these double values appear in brackets. It is evident that the differences in these bracketed values are so small that circles passing below the toe might well have been neglected. An exception to this statement rests in the case of $\phi=0$ and $i<53°$, which is yet to be discussed. Where the circle passes below the toe the value of n is given in the table. When $y > x$ the lowest point on the rupture arc is at a lower elevation than the toe of the slope, and thus the existence of an underlying ledge or other surface of high shearing strength might have an effect on the Stability Number. The values of D (see key sketches of Fig. 8), which describe the depth to the lowest point of the rupture arc, are given in the table for all cases where $y > x$.

The final column of Table I gives the value of the Stability Number after the ϕ-circle correction has been applied. Returning now to the discussion of the ϕ-circle assumption, this correction will be described.

The distribution of the p forces (Fig. 1 (a)) is indeterminate, but investigations may be made for various assumed distributions. If k represents the ratio by which the moment arm of the force P exceeds the radius of the ϕ-circle, it may be shown that —

(a) Assuming a constant intensity of p forces —

$$k=\frac{y}{\sin y}-1$$

wherein y is half the central angle at the arc, as shown in Figs. 1 (a) and 2 (a).

(b) Assuming intensity of p force equal to zero at A and B and varying sinusoidally between —

$$k=\frac{1-\left(\frac{2y}{\pi}\right)^2}{\cos y}-1$$

For a given distribution assumption, k depends only on the central angle $2y$, and the relation between k and $2y$ is plotted in Fig. 2 for cases (a) and (b).

In all probability, assumption (a) is not even approximately correct, while assumption (b) is close enough to the actual to describe k with reasonable accuracy. By referring to the critical values of y as given in Table I, it may be seen that the highest value k will ever attain for cases where $\phi > 0$ is about 7 per cent.

It is of especial interest to note that the line of action of P as obtained by the use of the ϕ-circle assumption would be strictly correct for some slightly smaller value of ϕ; thus the assumption exactly corresponds to using a slightly conservative value of ϕ. Instead of the ϕ-circle, a circle of slightly larger radius should be used, and on this basis a correction which will be called the ϕ-circle correction may be

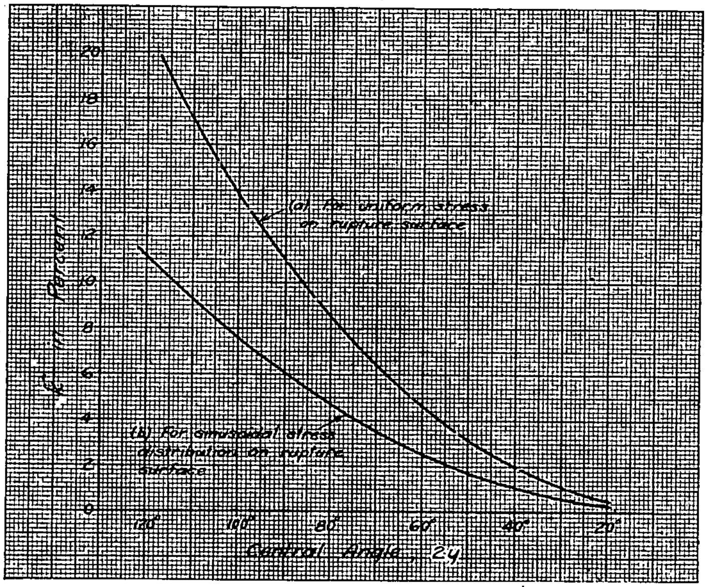


FIG. 3. — CHART FOR DETERMINATION OF FACTOR "K" IN THE ϕ-CIRCLE CORRECTION

made by the use of the k values of Fig. 3, curve (b). As an example, for $i=30°$ and $\phi=15°$, Table I gives $\frac{c}{FwH}=.049$ and $y=39°$; hence from Fig. 3, $k=4.5\%$. The radius of the ϕ-circle is $R \sin \phi$. If the corrected circle of slightly larger radius, $R \sin \phi'$, is introduced, the following is the relationship which must hold:

$$R \sin \phi' = R \sin \phi \ (1+k)$$

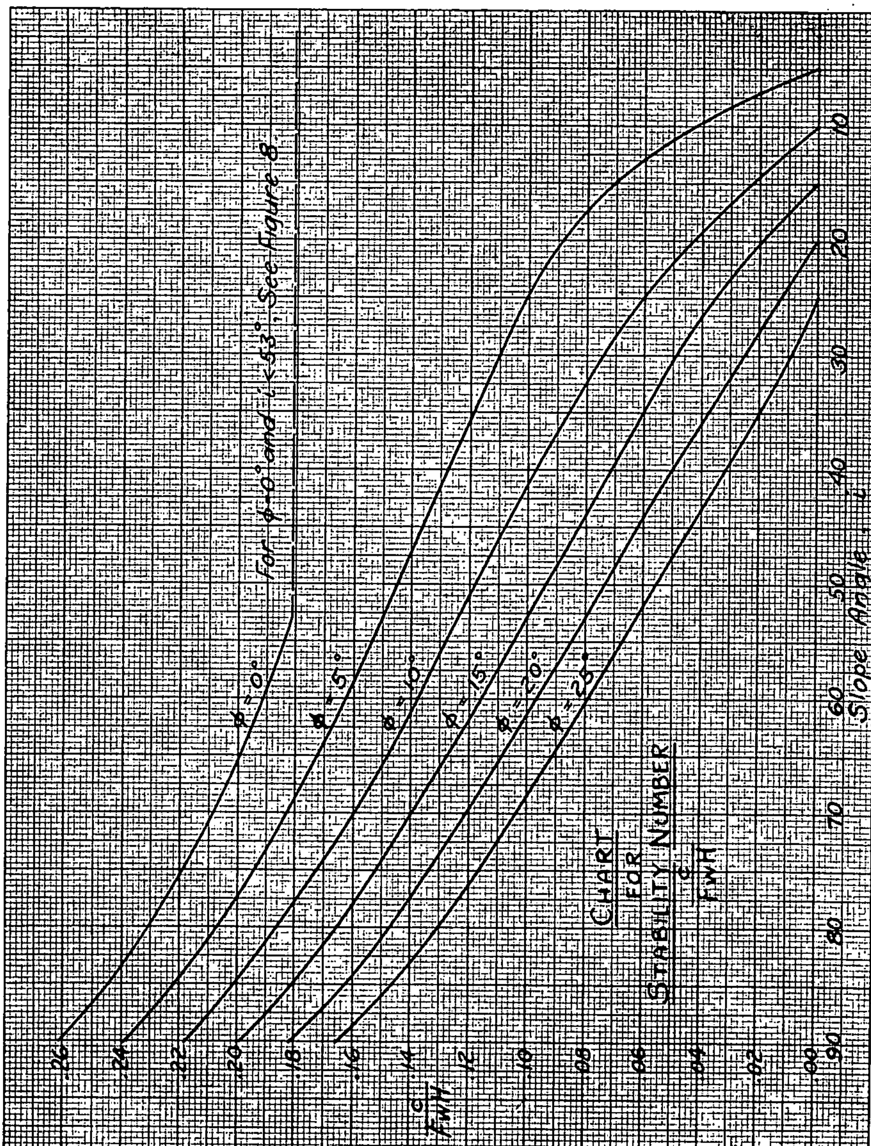

For φ=0° and i<53°, See Figure 8
φ=0°
φ=5°
φ=10°
φ=15°
φ=20°
φ=25°
CHART
FOR
STABILITY NUMBER
c/FWH
c/FWH
.26
.24
.22
.20
.18
.16
.14
.12
.10
.08
.06
.04
.02
.00
90
80
70
60
50
40
30
20
10
Slope Angle i

FIG. 4

By solving, $\phi' = 15° - 42'$, and by interpolation in Table I, for $i = 30°$ and $\phi = 15° - 42'$, $\dfrac{c}{FwH} = .046$, which is the corrected value. From a practical viewpoint, the original value of $\dfrac{c}{FwH} = .049$ is slightly conservative and sufficiently accurate. The correction is never larger than in this illustrative case, and it is evident from the above equation that the correction vanishes when $\phi = 0$.

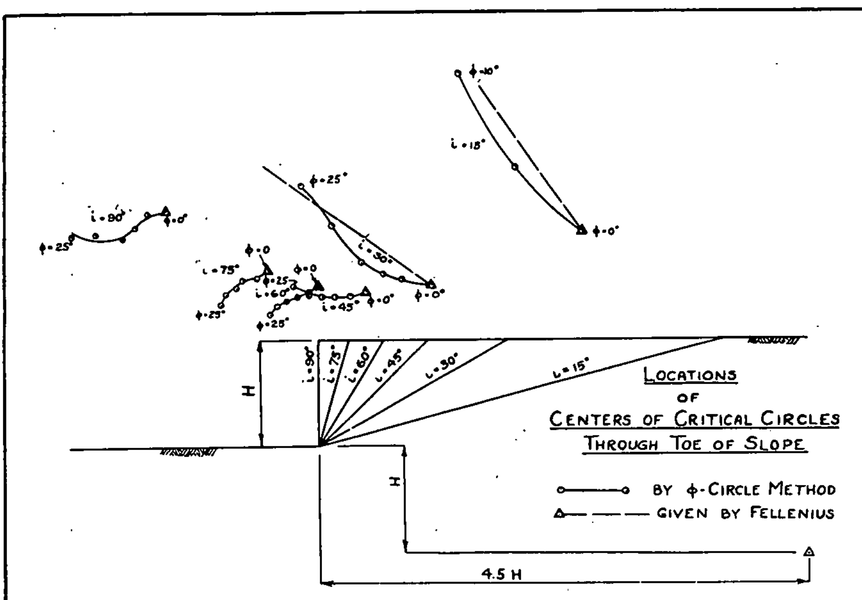


Fig. 5

The corrected values of Stability Number in the last column of Table I are accurate to three figures of decimals, which should always be sufficient for stability of slopes problems.

After the ϕ-circle correction has been applied, a rewording of the assumption involved should be made. The assumption that the force P is tangent to the ϕ-circle is replaced by the assumption that the distribution of the force P along the rupture is sinusoidal.

In Fig. 4 the results are presented as a nest of curves which allows easy interpolation. These curves give the critical values irrespective of the depth below the surface to which the critical circle may pass, and thus may be conservative if there is any limitation in this depth.

The co-ordinates describing the critical circles, as tabulated in Table I, are used for plotting Fig. 5, which shows the location of centers of most dangerous circles through the toe of the slope. As the majority of these centers were located only to the nearest degree in x and y, it may be noted that the plotting of the points is a bit irregular. This is, however, of no real importance. The data given by Fellenius for the locations of critical centers for circles through the toe consist of locations of centers for cases where $\phi=0$, together with the information that for flat slopes, when $\phi > 0$, the center will be approximately on a line through the point for $\phi=0$ and through a point at a depth H below and 4.5 H back from the bottom point of the slope. These points are plotted in Fig. 5 by triangles and the lines shown broken. As is to be expected, since Fellenius' work for $\phi=0$ was carried out mathematically, it checks exactly with the $\phi=0$ values of Table I. For slopes of 30 degrees and less the line given is also in fairly good agreement. For slopes of greater than 30 degrees, Fig. 5 would tend to show that this line begins to deviate appreciably from the most dangerous center, but it still may be used without serious error for slopes up to about 60 degrees as is indicated in Fig. 6. This figure shows the contouring of $\frac{c}{FwH}$ values with respect to the centers used, for $i=60$ and $\phi=20°$. Any point on the contour marked .090, if used as a center, gives $\frac{c}{FwH}=0.090$, and any point within this closed curve represents a value between .090 and the critical value .098. Thus any point within this rather large area, if used as a center, will give a value which will not differ from the critical value by more than 9 per cent. A line on the basis of that given by Fellenius is also shown on the figure, and, while it misses the critical point by an appreciable amount, it may be seen that the maximum along this line is .095, which is only 3 per cent below the critical value. On this same figure the traces obtained for the critical failure planes by the ϕ-Circle, Culmann and Jáky Methods are shown. The ϕ-circle correction has not been applied in Fig. 6. However, in all other figures applying to the ϕ-Circle Method, in which the Stability Number appears, this correction has been made.

When the effective friction angle is equal to zero, an unusual condition is met which requires special attention, as was pointed out by Fellenius as early as 1918. Mathematical analysis shows that there is a maximum value of the Stability Number which is independent of the slope angle and is equal to 0.181; which occurs when angle x is zero and the rupture surface has infinite radius and passes an infinite distance below the toe of the slope.

Zero friction angle and constant cohesion must mean constant shearing strength regardless of depth, a situation which cannot be pos-

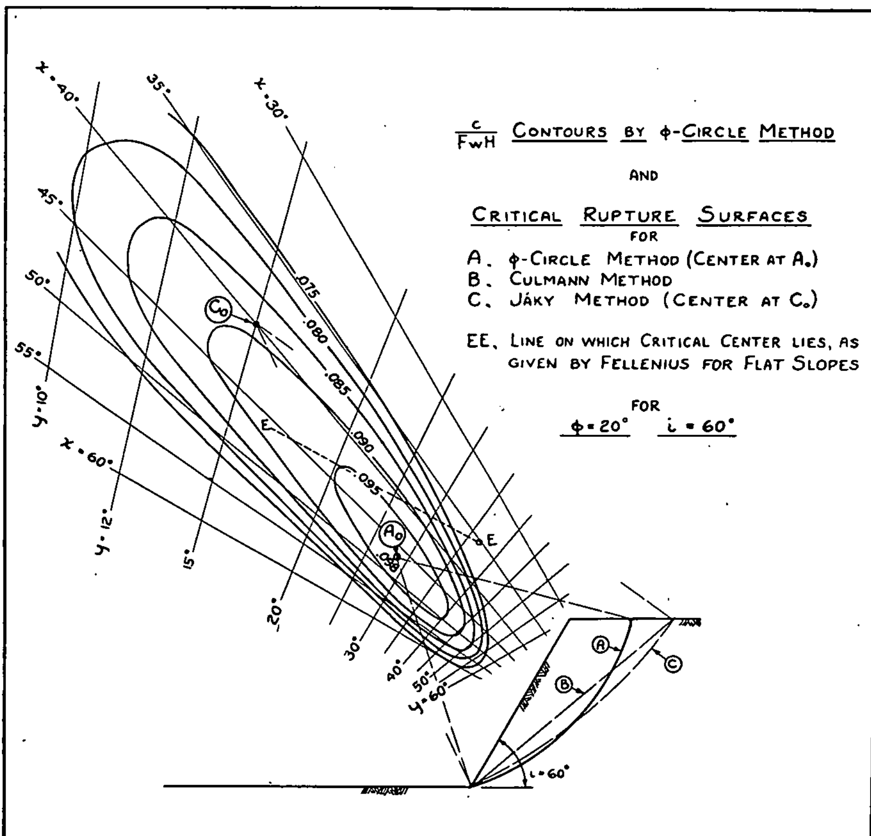


Fig. 6

sible to infinite depth. However, the shearing strength of embankments may often be essentially constant down to some definite strata of higher strength; for instance, to hardpan or ledge. Furthermore, the above maximum condition must mean that the Stability Number will increase with depth; thus to analyze such cases the relation between Stability Number and the available depth within which rupture may occur must be known.

Although this maximum value is independent of the slope, there is the maximum value for circles through the toe which occurs as shown in Fig. 5. This maximum through the toe gives Stability Numbers which are greater than 0.181 for slopes steeper than 53 degrees; thus the study of deep-seated rupture arcs is confined to slopes of less than 53 degrees. Fellenius called attention to the fact that for $\phi=0$ and slopes flatter than 53 degrees, the critical circle passes below the toe and has its center above the mid-point of the slope. He also gave data computed by mathematical solution for this case with a uniformly distributed surcharge at the top of the slope, but these data are limited to cases of vertical slope and values of depth factor D of 1, 1.5 and 2. In developing a complete solution of this case for the simplified conditions adopted in this paper, the following formulas were used. It should be noted that the ϕ-circle assumption does not enter when $\phi=0$.

When $\phi=0$, equation (12) reduces to —

$$\frac{c}{FwH}=\frac{\sin^2 x \sin^2 y}{2y}\left[\frac{1-2\cot^2 i}{3}+\cot x \cot y+\cot i\,(\cot x-\cot y)\right] \quad (18)$$

This simplified formula, in almost exactly the same form, was given by Fellenius.

Equation (13) becomes —

$$n=\frac{1}{2}\,(\cot x-\cot y-\cot i) \quad (19)$$

and for circles below the toe, equation (7) becomes —

$$\frac{c}{FwH}=\frac{\sin^2 x \sin^2 y}{2y}\left[\frac{1-2\cot^2 i}{3}+\cot x \cot y+\cot i\,(\cot x-\cot y)+2n^2\right] \quad (20)$$

or —

$$\frac{c}{FwH}=\frac{1}{4y}\left[\sin^2 x+\sin^2 y-\frac{2-\cot^2 i}{3}\sin^2 x \sin^2 y\right] \quad (20a)$$

From Fig. 2 (a):

$$D=\frac{1}{2}\,(\csc x \csc y-\cot x \cot y+1) \quad (21)$$

in which D may be designated as depth factor, and from which —

$$\csc x = (2D-1)\csc y + 2\sqrt{D^2-D}\cot y \qquad (22)$$

For any chosen value of D, there is only one degree of freedom involved in the problem to be solved, since for any assigned value of y the value of x is available from equation (22). For critical circles through

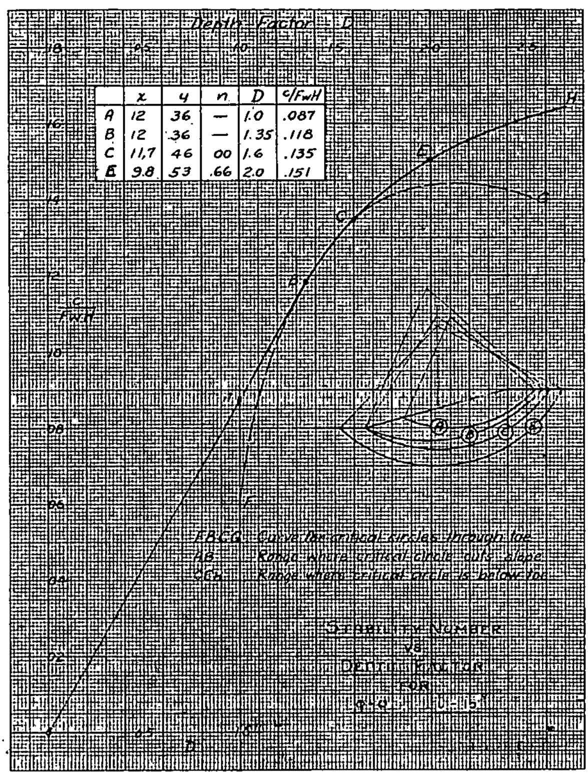


FIG. 7

the toe, by the use of equations (22) and (18), a curve of Stability Number against depth factor D may be obtained.

In Fig. 7, line $FBCG$ represents this condition for $i=15°$. However, after equation (22) is evaluated, equation (19) should be tried, since positive values of n indicate a critical circle below the toe. If n is positive, as it will be for sufficiently high values of D, equation (20)

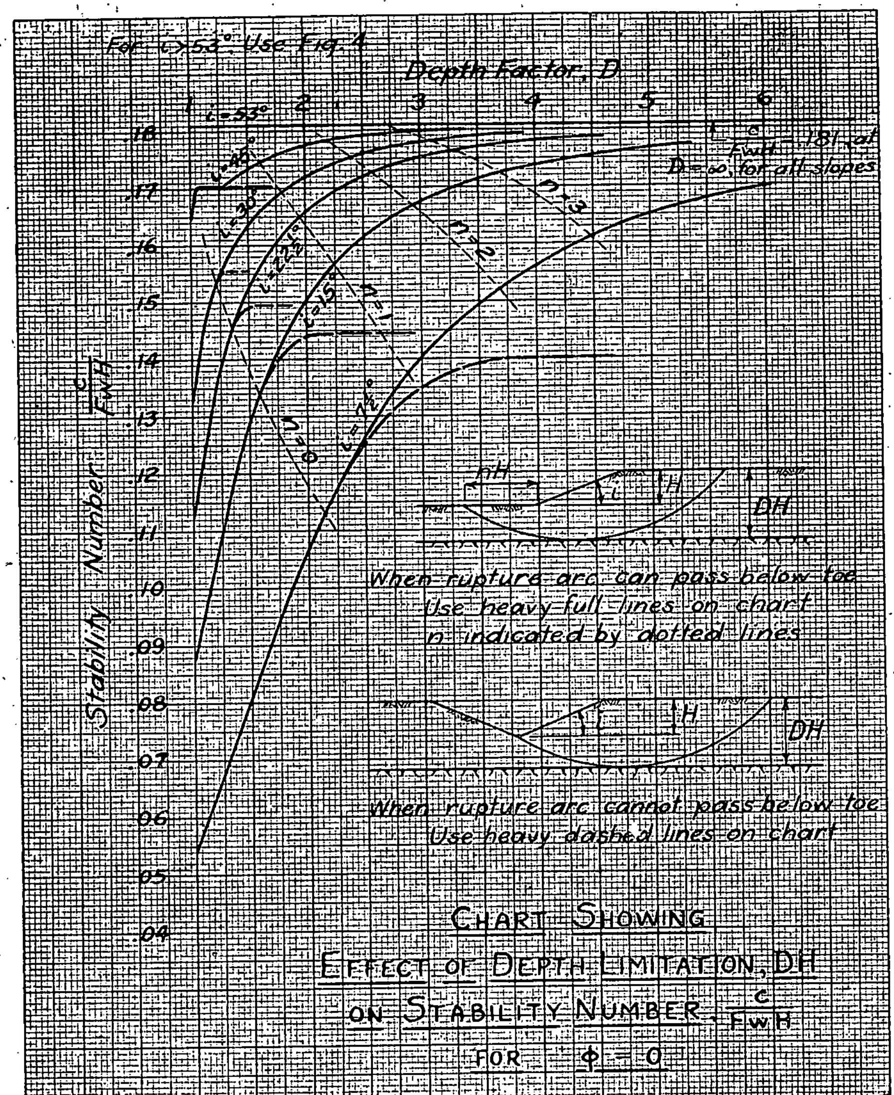

For i>53° Use Fig. 4
Depth Factor, D
1 2 3 4 5 6
i=53°
i=45°
i=30°
i=22½°
i=15°
i=7½°
n=0
n=1
n=2
n=3
c/FwH = .181 at D=∞ for all slopes
Stability Number c/FwH
.18 .17 .16 .15 .14 .13 .12 .11 .10 .09 .08 .07 .06 .05 .04
nH
i
H
DH
When rupture arc can pass below toe
Use heavy full lines on chart
n indicated by dotted lines
When rupture arc cannot pass below toe
Use heavy dashed lines on chart
CHART SHOWING
EFFECT OF DEPTH LIMITATION, DH
ON STABILITY NUMBER c/FwH
FOR φ = 0

FIG. 8

or (20*a*) should be used instead of equation (18). Line *CEH* of the figure is the desired curve for the critical circle, in the range where this circle is below the toe.

If a rigid surface should exist at the level of the base of the slope, it is natural to expect a possible rupture arc passing above the toe of the slope. In such a case the ruling height is the depth to ledge, and

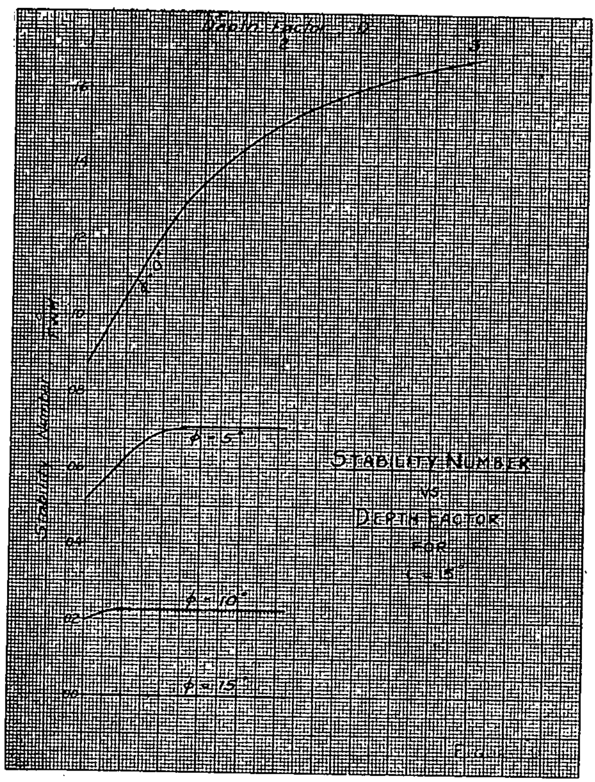


FIG. 9

the actual height of the slope is not important. In Fig. 7, if a line is drawn through the origin, tangent to the curve, this line, *AB*, is the required curve within the range where the most dangerous circle passes above the toe of the slope. For a mathematical approach within this range, it could be shown that x and y should be chosen so that the right-hand side of equation (18) divided by the right-hand side of equation (21) is a maximum. In the sketch of Fig. 7 the rupture arcs for points

A, B, C and E are drawn, while the data pertaining to them are given in the table. Fig. 8 presents a nest of curves of this type, covering the range of slopes from 7½ degrees to 53 degrees. The possibility of a failure through the toe of the slope may exist even though the critical circle is below the toe, if the material outside the toe is loaded in some manner. Such a case is indicated by the lower sketch of the figure, and the dashed lines provide values which may be used when such situations occur. Values of n may be obtained from the chart for cases where the critical arc is below the toe, and may be of some value in predicting the approximate outer edge of the mud wave which would be formed in case of failure. It must be noted, however, that if n is limited instead of d, an entirely different problem is presented, and this chart cannot be used to determine the Stability Number; an exception being that if n is restricted to a value of zero the dashed curves are applicable.

Reference to the depth factor column in Table I shows that the available depth may have some effect on the Stability Number when $\phi > 0$ and i is small. This effect is quite pronounced when $i = 15°$, and still exists when $i = 30°$. For $i = 15°$, Fig. 9 presents a solution of the effect of the depth factor.

The above derivations assume that an obliquity of ϕ is developed at all points along the rupture arc, or, in other words, that all available friction is utilized. If a part of this friction is not developed, there remains an excess of unused strength which represents a factor of safety with respect to friction. If at any point on an arc this factor with respect to friction is F_F, then the obliquity of stress, ϕ_D, which is developed across the arc at this point, is described by the following equation:

$$\tan \phi = F_F \tan \phi_D$$

and it may be noted that it will usually be sufficiently accurate to use the relation —

$$\phi_D = \frac{\phi}{F_F}$$

A constant value for ϕ_D would probably never occur simultaneously at all points of the arc because of the progressive nature of the development of the shear. Thus ϕ_D for any given arc must be described as the average developed obliquity, or the obliquity which, were it constant, would lead to the same total frictional shearing stress as actually is developed.

The friction angle ϕ, as used up to this point, was also the developed obliquity. If a true factor of safety, F_T, is desired, this factor to apply to both cohesion and friction, then the developed obliquity must be $\phi \div F_T$. If the value of ϕ in all the preceding derivations is superseded by the more general value of ϕ_D, then the factor of safety which was previously only relative to the cohesion becomes the true factor F_T. This replacement of ϕ by ϕ_D and F by F_T applies not only to all formulas but also to Figs. 4, 8 and 9. It could be demonstrated that any small change in the validity of the ϕ-circle assumption, because of ϕ_D being an average rather than a constant value, is probably favorable. Expressed mathematically, the above may be summarized as follows:

$$\frac{c}{FwH} = f\ (i,\ \phi) \quad \text{and} \quad \frac{c}{F_T wH} = f\ (i,\ \frac{\phi}{F_T})$$

Applications of both types of safety factors will be found in the illustrative problems. For the typical cohesive soil the effective cohesion can be determined with at least as good accuracy as the effective friction angle. Thus it will seldom be logical to use the factor of safety with respect to cohesion in preference to the true factor of safety.

The Logarithmic Spiral Method

In the Circular Arc Method it is necessary to introduce some assumption to make the problem statically determinate. To avoid this undesirable feature, Rendulic recommended the use of a logarithmic spiral as the surface of rupture.

The important property of the logarithmic spiral, expressed in polar co-ordinates by the equation —

$$r = r_1 {}^{\theta \tan \phi} \qquad (1)$$

is that all radius vectors cut the curve at an angle of obliquity of ϕ. In Fig. 10 (a) such a curve is represented by the line ACB, r being equal to r_1 at OA where θ equals zero. As the forces on elements along the rupture surface must have an obliquity of ϕ, it may immediately be seen that with the use of this curve all elementary forces across the rupture surface, as well as their resultant force, must be directed toward the pole O. It should be noted that θ must increase counterclockwise in this figure, as the obliquity must be such as to resist a slide.

As in the circular scheme, there are two degrees of freedom in the logarithmic spiral. These will be taken as the central angle z and the chord slope t. A number of sets of values of these two variables must be tried until the critical location is obtained.

The principal steps in the mathematical solution are given below. As in the previous derivation, F is the factor of safety with respect to

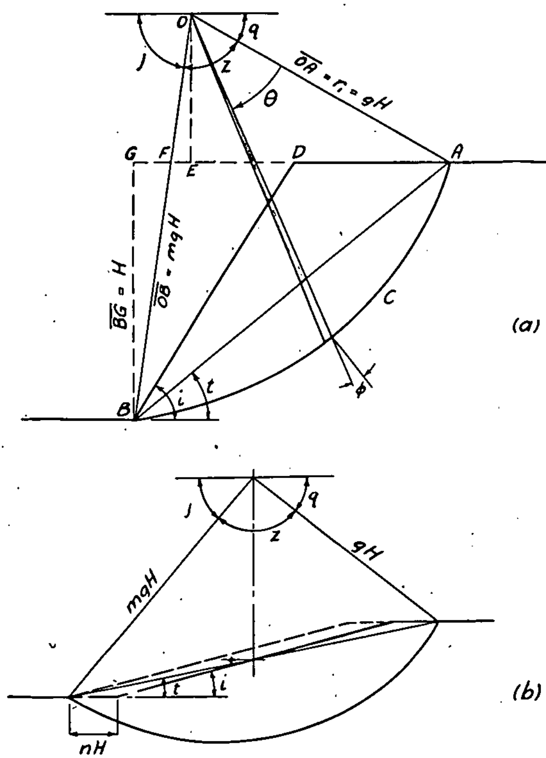


FIG. 10. — SKETCHES SHOWING ELEMENTS OF THE LOGARITHMIC SPIRAL METHOD

cohesion, but the solution is applicable for use with the true factor of safety as explained.

Four dependent variables are used to simplify the solution. They are as shown in Fig. 10, and are described by the following expressions, which hold for the curve either through or below the toe of the slope:

$$m = e^{z \tan \phi} \tag{2}$$

$$g = \frac{1}{\sin t\sqrt{1+m^2-2m\cos z}} = \frac{r_1}{H} \tag{3}$$

$$j = t + \sin^{-1}\left[\frac{\sin z}{\sqrt{1+m^2-2m\cos z}}\right] \tag{4}$$

$$q = \pi - z - j \tag{5}$$

Referring again to the three forces W, C and P, and taking moments about the pole, there results —

$$M_w + M_{c_1} = 0 \quad \text{or} \quad M_w + \frac{M_c}{F} = 0 \tag{6}$$

where

$$M_c = -\int_0^z c\, r^2\, d\,\theta = -\frac{c\, g^2\, H^2}{2 \tan \phi}(m^2-1) \tag{7}$$

and for the curve through the toe of the slope —

$$M_w = M_1 - M_2 - M_3 \tag{8}$$

in which M_1, M_2 and M_3 are moments about O for the masses represented by areas $OACB$, OAF and BDF, respectively, of Fig. 10 (a).

$$M_1 = w\int_0^z \frac{r^3}{3}\cos(\theta+q)\,d\theta = \frac{wg^3H^3}{3\,(9\tan^2\phi+1)}\left[(m^3\sin j-\sin q) - 3\tan\phi\,(m^3\cos j+\cos q)\right] \tag{9}$$

$$M_2 = \frac{1}{6}wg^3\,H^3\sin^3 q\,(\cot^2 q - \cot^2 j) \tag{10}$$

$$M_3 = \frac{1}{6}wH^3\left[\cot^2 i - \cot^2 j - 3mg\cos j\,(\cot i - \cot j)\right] \tag{11}$$

Substituting (7), (9), (10) and (11) in (8) and (6) gives —

$$\frac{c}{FwH} = \frac{\tan\phi}{3g^2\,(m^2-1)}\left[\frac{2g^3\left\{(m^3\sin j - \sin q) - 3\tan\phi\,(m^3\cos j + \cos q)\right\}}{9\tan^2\phi + 1} + \right.$$

$$\left. + g^3\sin^3 q\,(\cot^2 j - \cot^2 q) + 3mg\cos j\,(\cot i - \cot j) - \cot^2 i + \cot^2 j\right] \tag{12}$$

Equation (12) applies when the rupture curve passes through the toe of the slope. When it passes below the toe, the most dangerous condition is obtained when the mid-point of the slope is vertically below the origin, and from Fig. 10 (b) —

$$n = mg \cos j - \frac{1}{2} \cot i \qquad (13)$$

The increase in overturning moment as compared to the previous case is —

$$\frac{1}{2} wn^2 H^3 = \frac{wH^3}{2} (mg \cos j - \frac{1}{2} \cot i)^2$$

which, when included in equation (8), leads to the following alternate for equation (12):

$$\frac{c}{FwH} = \frac{\tan \phi}{3g^2 (m^2 - 1)} \left[\frac{2g^3 \left\{ (m^3 \sin j - \sin q) - 3 \tan \phi \, (m^3 \cos j + \cos q) \right\}}{9 \tan^2 \phi + 1} + \right.$$

$$\left. + g^3 \sin^3 q \, (\cot^2 j - \cot^2 q) + 3mg \cos^2 j \, (mg - \csc j) - \frac{1}{4} \cot^2 i + \cot^2 j \right] \qquad (14)$$

For any chosen values of z and t the dependent variables may be obtained from (2) to (5), inclusive, after which n may be evaluated by the use of (13). If n is negative, (12) must be used, while for positive values of n, (14) will give the greater value for the Stability Number.

It was found that a computation by this method requires about twice as long as one by the ϕ-Circle Method. For the critical values of the Stability Number, it developed that z and t, the central angle and chord slope for the Spiral Method, are approximately equal to the corresponding critical values, $2y$ and x of the ϕ-Circle Method. (See Table III.) This was of assistance in choosing points for trial computation by one method after the work of the other was completed. Because of the large amount of labor involved, the computations for the Spiral Method have been carried out for only enough representative cases to give a good comparison with results by the ϕ-Circle Method. These comparisons are given later.

Comparison of Methods

The general formula for the Culmann Method may be expressed as follows:

$$\frac{c}{FwH}=\frac{1-\cos\,(i-\phi)}{4\,\cos\,\phi\,\sin\,i}$$

By the Résal-Frontard Method, the depth to which tension exists, y_o, and the general formula expressed in the form of the Stability Number are —

$$y_o=\frac{2c}{w}\tan\,(45+\frac{\phi}{2})$$

$$\frac{c}{FwH}=\frac{\sin\,(i-\phi)}{2\,\sin^2 i\,\cos\,\phi}\left[\frac{1}{\dfrac{\cos\,\phi}{\sin\,i\,(1-\sin\,\phi)}+\dfrac{\cos^{-1}\left\{\dfrac{\sin^2 i-\sin\,\phi}{\sin i\,(1-\sin\,\phi)}\right\}}{\sqrt{\sin\,(i-\phi)\,\sin\,(i+\phi)}}}\right]$$

The general mathematical expression as given by Jáky is too long to be reproduced here. However, his final results (9*c*) are submitted in the form of an expression $f\,(\beta)$ where —

$$\frac{c}{FwH}=\frac{1}{4}\frac{1}{f\,(\beta)}$$

Table II presents the results of computations for $\frac{c}{FwH}$ by the three above-mentioned methods, and also by the ϕ-Circle Method for rupture arcs through the toe of the slope. Where more dangerous circles exist passing below the toe, the values by the ϕ-Circle Method are given in parentheses. The ϕ-circle correction has not been applied in this table nor in the figure which follows. For the case $\phi=10°$ the results are plotted in Fig. 11, and the relationships between different methods as shown in this figure are very similar for any other value of ϕ. This figure illustrates the statement made previously, that the Culmann Method gives low values, while the Résal-Frontard Method gives results which are much too high. The values obtained by the ϕ-Circle Method and the Jáky Method show reasonably close agreement, and

TABLE II

VALUES OF $\frac{c}{FwH}$ BY VARIOUS METHODS

Slope Angle (i)	Friction Angle (φ)	Résal-Frontard (1)	Culmann (plane) (2)	Jáky $\frac{1}{4f(\beta)}$ (3)	Jáky Circle-φ-Circle Method (4a)	φ-Circle (4)
90 . . .	0	.500	.250	–	–	.261
	5	.458	.229	.229	.229	.239
	10	.420	.210	.210	.210	.218
	15	.384	.192	.192	.192	.199
	20	.350	.175	.175	.175	.182
	25	.319	.159	.159	.159	.166
75 . . .	0	.396	.192	–	–	.219
	5	.353	.171	.172	.183	.195
	10	.307	.152	.156	.163	.173
	15	.280	.134	.135	.144	.153
	20	.246	.117	.119	.126	.135
	25	.215	.102	.102	.110	.118
60 . . .	0	.328	.144	–	–	.191
	5	.284	.124	.135	.149	.163
	10	.244	.105	.116	.127	.139
	15	.208	.088	.098	.107	.118
	20	.174	.072	.081	.089	.098
	25	.143	.058	.063	.073	.081
45 . . .	0	.280	.104	–	–	(.170)
	5	.231	.083	.109	.121	.138
	10	.187	.065	.086	.097	.110
	15	.148	.049	.064	.075	.086
	20	.113	.035	.044	.057	.065
	25	.081	.023	.028	.041	.046
30 . . .	0	.244	.067	–	–	(.156)
	5	.183	.047	.082	.095	(.112)
	10	.130	.031	.051	.066	.078
	15	.085	.018	.027	.042	.049
	20	.047	.008	small	.022	.027
	25	.017	.002	0	.005	.010
15 . . .	0	.217	.033	–	–	(.144)
	5	.118	.015	.035	.059	(.072)
	10	.043	.004	0	.019	(.024)

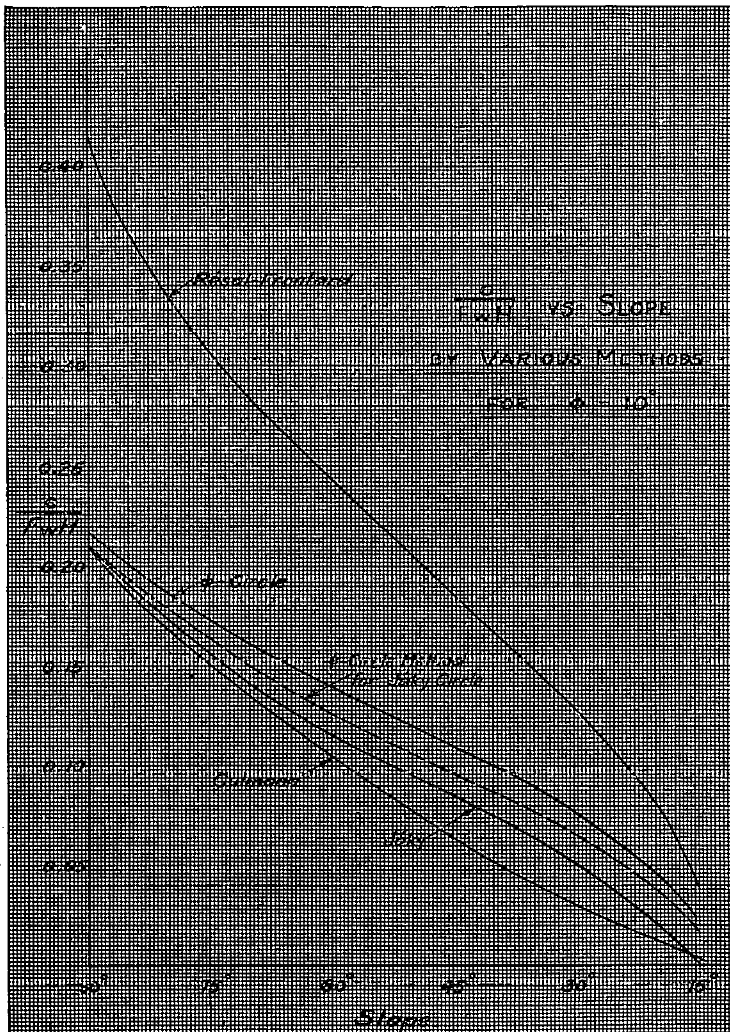


FIG. 11

the difference is of little practical importance in computations of this type. The most questionable step in the Jáky Method is in the choice of critical circle, and if Jáky's circle is used in a computation by the ϕ-Circle Method the results given in Table II, column (4a), and the dotted curve of Fig. 11 are obtained. While it must be remembered that different assumptions may lead to different critical circles, there is at least an indication here that Jáky's choice of circle is questionable, and the results by his method are slightly low.

A comparison of results by the general mathematical solution based on the ϕ-Circle Method, and Fellenius' general solution by graphics using the Slices Method, is given in Table III. It may be seen that the

TABLE III

COMPARISON OF VALUES OF $\frac{c}{FwH}$ BY SLICES AND ϕ-CIRCLE METHODS.

i	$\phi=5$		$\phi=15$		$\phi=25$	
	Slices	ϕ-Circle	Slices	ϕ-Circle	Slices	ϕ-Circle
15	.072	.070	–	–	–	–
30	.114	.110	.048	.046	.012	.009
45	.141	.136	.085	.083	.048	.044
60	.165	.162	.120	.116	.082	.079
75	.196	.195	.154	.152	.118	.117
90	.239	.239	.199	.199	.165	.166

two solutions agree closely. The values by the Slices Method are slightly higher throughout, which checks the claim that the assumption used in the Slices Method is conservative.

Fellenius stated that for the steeper slopes the assumption of plane failure is not appreciably in error, thus there is little need to determine locations of critical circles for steep slopes. This is true only to a limited degree, as may be seen by comparison of columns (2) and (4) of Table II. As an example, it may be noted that on the basis of plane failure for $i=60$ and $\phi=20$ the Stability Number is about 25 per cent on the unsafe side as compared to the assumption of circular rupture arc.

For the cases for which computations have been made by both the ϕ-Circle and Spiral Methods, the comparisons given in Table IV are obtained. It is evident that for all practical purposes the results by the

TABLE IV

COMPARISON OF RESULTS BY THE ϕ-CIRCLE AND THE LOGARITHMIC SPIRAL METHODS

i	ϕ	ϕ-Circle Method			Logarithmic Spiral Method		
		Chord Slope x	Central Angle $2y$	$\frac{c}{FwH}$	Chord Slope t	Central Angle z	$\frac{c}{FwH}$
90	25	60	22	.1659	61	22	.1651
60	25	50	60	.0788	49	58	.0784
30	25	29	50	.0089	29	40	.0083
60	15	44	63	.1160	44	60	.1159
90	5	50	28	.2386	50	29	.2387
60	5	38.5	69	.1624	39	69	.1624
15	5	(12.5)	(94)	(.0682)	(13)	(88)	(.0681)
15*	5	11	95	.0695	11.7	92	.0696

* Indicates critical rupture surface passing below toe of slope: by ϕ-Circle Method $n = .55$; by Logarithmic Spiral Method $n = .40$.

two methods are identical. Fig. 12 illustrates the very close agreement for a typical case.

The conclusion may be drawn that because of its requiring no further assumption, the Spiral Method is the preferable of the two, at least from a theoretical viewpoint. However, the greater length of time required for computation more than overbalances this preference, and the final results given by this paper (Fig. 4) are figured by the ϕ-Circle Method. It may be noted that these two methods and the Slices Method as well become identical for the case of $\phi = 0$.

EFFECTS OF SATURATION AND SEEPAGE

To study the various possible conditions to which a slope may be subjected, the following stages may be pictured:

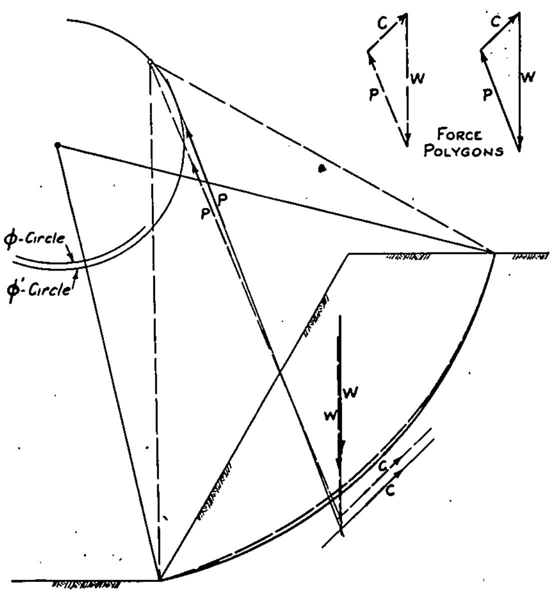
A. Complete Submergence. — Free water level at top of slope, soil fully saturated.

B. Sudden Drawdown. — Case A, with free water suddenly removed.

C. Steady Seepage. — Continuous flow of water through the soil, requiring a constant supply of ground water or rainwater to maintain seepage.

D. Capillary Saturation. — No flow of water, no supply, no evaporation. Pores of soil filled with water held by capillarity, a condition common in typical cohesive soils.

Conditions other than the above, such as complete or partial drying, may also prevail. Here the problem is of an entirely different nature, involving prevention of disintegration rather than considera-



ϕ-Circle Method shown by full lines.
Logarithmic Spiral Method shown by dash lines.

FIG. 12. — COMPARISON OF ϕ-CIRCLE AND LOGARITHMIC SPIRAL METHODS FOR $\phi = 15°$; $i = 60°$

tion of stability (9*b*). Also an indefinite number of intermediate states will occur in passing from one to another of those above outlined.

Cases A and D will be developed first, since they are important from the practical viewpoint and are easily handled.

A. Complete Submergence

The unit weight which is to be used in connection with the Stability Number for this case is the submerged unit weight, given by the expression $\frac{s-1}{1+e} w_o$, where s is the specific gravity of the solid particles of the soil, e is the void ratio or ratio between volume of voids and volume of solid matter, and w_o is the unit weight of water. For the general run of soils the submerged unit weight will be in the vicinity of 50 to 70 pounds per cubic foot. This low unit weight means that this case is the most favorable that can be obtained; therefore the submerged case cannot be assumed with safety for stability analyses unless permanent submergence is assured. With the use of the saturated unit weight, the equilibrium polygon of Fig. 1 (*b*) is applicable and no complications enter. It is to be noted that protection against such items as wave action are important but do not come within the scope of this paper.

D. Capillary Saturation

The unit weight which applies for this case is the total unit weight, that is, the weight of both solids and water, which is given by the expression $\frac{s+e}{1+e} w_o$. Its value will generally be in the neighborhood of 110 to 130 pounds per cubic foot. Compared to the saturated case, the unit weight for this case is approximately twice as large, thus the force W of Fig. 1 (*b*) would be about doubled, and the required shearing strength must also be about twice as great. However, the use of this case, where there is a possibility of future seepage within the slope, is not safe, as seepage introduces forces which lead to a still more unfavorable situation.

Where there is seepage of water through the embankment, or where there is the possibility of such seepage occurring at some season of the year, the development of a method for handling the situation is much more difficult. It has been suggested (9*a*) that flow nets may be sketched and from these a solution may be obtained. This involves the use of the tedious graphical trial method of solution plus the construction of the flow net. It can be demonstrated, however, that the shearing strength required for stability in case C, Steady Seepage, is greater than that in case D and less than that in case B; also that in many cases there is not a radical difference between the requirements of cases B and D. The percentages by which Stability Numbers for case D are less than those for case B are indicated in Table V, which shows that very large differences occur only for flat slopes with high friction angles. Thus the steady seepage case must represent a case somewhere within the rather narrow range between two cases for which computations may be made without difficulty. It can also be shown that, if submergence

TABLE V

PERCENTAGE BY WHICH STABILITY NUMBER FOR CAPILLARY SATURATION CASE IS LESS THAN STABILITY NUMBER FOR SUDDEN DRAWDOWN CASE FOR $\frac{s-1}{s+e}=\frac{1}{2}$

ϕ	Slope		
	90°	60°	30°
0°	0	0	0
10°	9	15	25
20°	17	30	65

or partial submergence ever occurs, subsequent drawdown may lead to a condition intermediate between cases B and C, and computations on the basis of case C would be unsafe.

These considerations lead to the recommendation that the requirements of case B, Sudden Drawdown, be used for slopes where there is seepage of water or any possibility of such seepage ever occurring. This is a procedure which is conservative, but which is probably sufficiently accurate for all cases of steep slopes and small friction angles. For cases where both flat slope and large friction angle occur, the bounding values as given by results for cases B and D may still be sufficient in many instances. It is doubtful if the accuracy which can be attached to stability computations is great enough to warrant the drawing of flow nets and the involved procedure that must follow, unless the difference between these bounding values is quite large.

A complete development of case C would require more space than can be allotted to it in this paper. An outline of the basic points involved would seem to be sufficient, and with this in mind points of theory behind such items as the principles of flow nets will be kept to the minimum. Later, a number of practical problems are given which will serve to illustrate various factors much better than any theoretical treatment could hope to do.

B. Sudden Drawdown

The force W of Fig. 1 (*b*) represents the effective weight of the sliding mass. For the submerged slope, Fig. 13 (*a*) shows the forces acting according to the ϕ-circle solution, wherein W_s, the effective weight for this case, equals the product of the area of the sliding mass and the submerged unit weight. The force polygon is shown in full lines in Fig. 13 (*b*). The corresponding diagram for the Capillary Saturation Case is shown in Fig. 13 (*c*), in which the effective weight W_T is based upon the total unit weight (soil plus water). The difference between the forces W_T and W_S will be designated by W_o, and it may be noted that this force is equal to the weight of a mass of water of the same total volume as the sliding mass. This weight W_o must be present in the submerged case, but it has no effect since it is just balanced by forces E_1 and E_2, the resultant water pressures across the slope and the rupture arc, respectively. Fig. 13 (*d*) shows the pressures which act along these surfaces; also the resultant forces E_1 and E_2 are shown in this figure, while the same forces appear dotted in the equilibrium polygon of Fig. 13 (*b*). E_2 must act normal to the slope at its lower third point, W_o must act vertically downward through the center of gravity of the sliding mass, and since the three forces, W_o, E_1 and E_2, are in equilibrium they must be concurrent. Since E_1 is made up of pressures which are everywhere normal to the rupture arc, and thus have no moment about the center of the circle, E_1 itself must have no moment about the center, and so must pass through O. Thus the lines of action of these three forces must be as shown in Fig. 13 (*e*). It may be noted that the moments of W_o and E_2 about O must just balance each other. It is correct to speak of W_o as an overturning force, but in this instance its overturning effect is just counterbalanced by the resisting effect of E_2.

The submerged case may be transformed into the sudden drawdown case by the sudden removal of the force E_2. Since the moment of E_2 just balances that of W_o, removal of E_2 introduces an additional overturning tendency equal to the moment of W_o. The weight W_o at the instant of sudden drawdown is carried by a temporary excess of pressure in the water, and intergranular stresses can replace this hydrostatic excess only as fast as the necessary strains in the mass can develop. Since W_o is not carried by the soil skeleton, no friction can be developed to help resist the shearing stresses it induces. Thus the overturning forces acting are W_o, which can be resisted only by cohesion, and W_S, which is resisted by cohesion and friction together. The force diagram for W_S alone is shown in Fig. 13 (*a*), while that for W_o, in which an effective friction angle of zero must be used, is given in Fig. 13 (*f*). Thus the cohesion required to overcome the combined overturning effects of W_S and W_o is the sum of C_S and C_o of Figs. 13 (*a*) and 13 (*f*).

A correct solution of this case would require trials on various rupture arcs for the determination of the critical value. The use of Fig. 4,

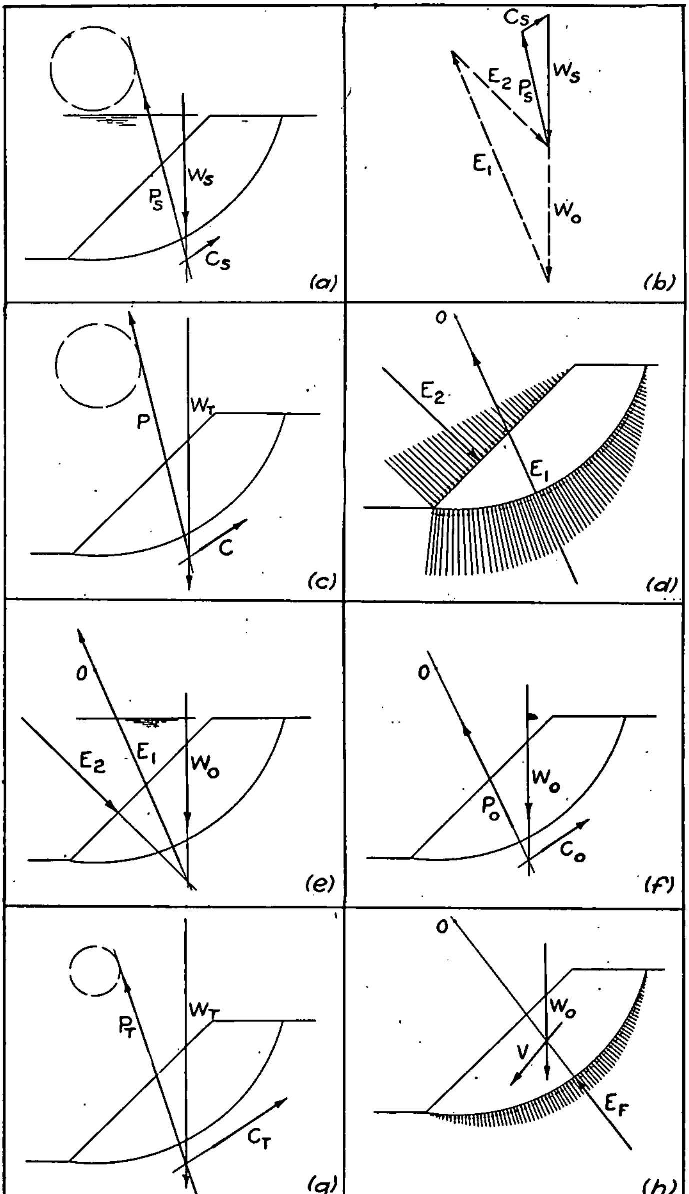

C_S
W_S
P_S
E_2
E_1
W_o
(a)
(b)
P
W_T
C
(c)
O
E_2
E_1
(d)
O
E_2
E_1
W_o
(e)
O
W_o
P_o
C_o
(f)
P_T
W_T
C_T
(g)
O
W_o
V
E_F
(h)

FIG. 13

with the two overturning forces handled separately, is not theoretically sound, as the two cases have different values of ϕ and thus will lead to different critical circles. A satisfactory method from a practical viewpoint is to use the total unit weight, with a weighted value for ϕ. The use of an arithmetically weighted value described by the following equation —

$$\phi_w = \frac{w_s}{w_s + w_o}\,\phi = \left[\frac{s-1}{s+e}\right]\phi$$

is not strictly correct, but the discrepancy involved will always be small. Fig. 13 (*g*) shows the use of a weighted value for ϕ, with W_T equal to W_S plus W_o. The required cohesion C_T equals the sum of C_S and C_o of Figs. 13 (*a*) and 13 (*f*).

It has been stated above that in the determination of cohesion and internal friction the conditions in nature must be reproduced as closely as possible in the laboratory tests. With this point in mind, for the sudden drawdown case it may be well to mention an alternate point of view to that given above. Let it be assumed that values for cohesion and friction have been determined for a case of a submerged slope. For the case of sudden drawdown a method of obtaining a weighted friction angle from these has been described. It may be possible that if another set of tests were to be run, using the conditions of consolidation, the time rate of shear, and other conditions, such as pressure on lateral planes which truly represent the situation, a value of ϕ might be obtained which would be a direct determination of that quantity which was obtained above by weighting. At present an accurate duplication of these natural conditions would be quite difficult, therefore the weighting scheme which offers a simple and conservative approximation is suggested.

The various possible stages have been discussed as if passing from one to another could occur without change of soil properties, but this may not be the case. The discussion of these stages aims to give a picture of the general situation. In addition to changes in this picture there will also be changes in the soil properties which must be covered by tests for cohesion and friction-angle under conditions which as nearly as possible reflect the actual natural conditions.

When the force E_2 is suddenly removed, the relatively large unbalanced force E_1 will produce an upward and outward flow of water, which may result in piping. At this instant the piping tendency is worse than later, when steady flow has been established. However, the condition is a transient one, and if investigations for piping are made for the steady state of seepage they may cover the situation. Further discussion of the possibility of piping will not be attempted in this paper.

The sudden drawdown case must be looked upon as a transient condition which is in effect only momentarily. The pressures within the sliding mass immediately begin to undergo adjustments, and after a sufficient lapse of time the condition of steady seepage is approached.

If water is seeping through a soil there must be a loss of potential in the direction of flow, this loss representing the energy required to force the water through the voids. This lost head is transmitted by viscous friction to the grain structure of the soil, thus producing forces in the direction of flow. It is the occurrence of these seepage forces which complicates the stability analysis for this case. It could be demonstrated that the resultant seepage force for the entire sliding mass would be a force such as V, Fig. 13 (h). While this force is developing, there will be an adjustment of pressures along the rupture arc starting from the initial state shown in Fig. 9 (d) and continuing to the ultimate as in Fig. 9 (h), where their resultant is the force E_F. The vector sum of forces E_F and W_o must equal force V. If no friction could be developed to resist these forces, the stability analysis would be exactly as for the sudden drawdown case, consisting of W_S as analyzed in Fig. 9 (a) and W_o as in Fig. 9 (e), with one other force for each case (E_1 and E_F) which produces no moment. Since friction will act to help resist the overturning effects, the actual situation must be somewhat safer than the above. Therefore the steady flow case is more stable than the sudden drawdown case.

There are an infinite number of flow nets which are possible for any given slope, and forces E_F and V will vary for different nets. For any given net, E_F may be determined for a given arc, but a rather complicated graphical procedure is involved.

If the supply of seepage water is completely shut off the magnitude of the pressures along the rupture arc decreases further, this time to zero if sufficient time is allowed, and meanwhile the force V disappears. This leads to the still more favorable case of capillary saturation which has already been discussed.

Surface Cracking

Foremost among the items which bring uncertainty into slope stability problems is the possibility of cracking at the top of the slope. As is indicated by the Résal-Frontard Method, the soil at this point is in tension. This tension may be counterbalanced, temporarily, at least, by the internal pressure of the soil, but the danger of cracks developing is always a disturbing possibility. It is evident that the cohesion which has been assumed constant over the rupture surface should not be depended upon within the zone of cracking.

If there were any rational way of figuring the depth of this zone, the item would not be of such great concern. The Résal-Frontard Method gives an expression for the depth to which tension is in effect, but it must be remembered that this derivation is based on the assumption of an infinite slope, and there is question as to its reliability when used adjacent to a discontinuity of the slope. Moreover, cracking is of a progressive nature, aided by water and often by ice pressure, and so is not limited to this depth in which tension occurs.

For an approximate analysis of this item some estimate must be made as to the depth to which cracks may progress. This estimate must be based largely on judgment and inspection of the soil and the conditions at the site, with perhaps some weight given to the value as determined by the Résal-Frontard Method. From this estimated depth the percentage of arc not affected by cracking may be determined, and this may then be multiplied by the unit cohesion. The average value for unit cohesion thus obtained does not lead to a resultant cohesion which is parallel to the chord, but it may be assumed that it does, noting that more nearly exact ways of handling this item could be introduced if the accuracy were warranted.

Terzaghi has suggested (9*a*) that within the zone of cracking the possibility of water pressure should be recognized and another overturning force introduced into the computations to cover it. Such a force is in reality a portion of a force of the nature of E_1 of Fig. 13 (*d*) which is fully covered when the sudden drawdown case is used.

As a means to obtaining a better understanding of this phase of the problem, it would be of value if data on a large number of slopes could be compiled, which should include estimates of depths of cracking and data on factors of safety as given by stability computations. The present scarcity of knowledge on this subject can be overcome only by the use of generous factors of safety.

Illustrative Examples

(1) A vertical cut of 15 ft. is to be made in a clay on which tests give $w=110$ lb. per cu. ft., $\phi=10°$, $c=750$ lb. per sq. ft. It may be assumed that there will be no seepage of water.

(*a*) What is the factor of safety with respect to cohesion?

(*b*) What cohesion would be required to give a true factor of safety of the same magnitude?

(*c*) Will the cut need sheeting?

(*a*) From Fig. 4, for $\phi=10°$ and $i=90°$, $\frac{c}{FwH}=.218$

$$\frac{c}{FwH}=.218=\frac{750}{F\times110\times15};\ \text{whence } F=2.1$$

(*b*)
$$\phi_D=\frac{\phi}{F_T}=\frac{10}{2.1}=4.8°$$

For $\phi_D=4.8°$ and $i=90°$, Fig. 4 gives $\frac{c}{F_TwH}=.240$

$$\frac{c}{F_TwH}=\frac{c}{2.1\times110\times15}=.240;\ \text{whence } c=830\ \textit{lb. per sq. ft.}$$

(*c*) The small difference between given cohesion and the value in part (*b*) indicates the major portion of the shearing strength is cohesion. If the given value for cohesion is a dependable average value, the factor of safety is ample and no sheeting is needed.

(2) A 45° cut 20 ft. deep is to be made across flat land where the water table is just at ground surface. The soil has a specific gravity of 2.80 and a void ratio of 0.75. It is specified that the true factor of safety is to be 1.5. The effective angle of internal friction may be assumed to be constant and equal to 15°. What values of unit cohesion are required —

(*a*) With the cut submerged?

(*b*) With the cut unwatered and a steady state of seepage?

(*c*) After a drop in water table and with no seepage occurring?

(*a*) $w=\frac{s-1}{1+e}w_o=\frac{1.8}{1.75}\times62.5=64.3;\ \phi_D=\frac{\phi}{F_T}=\frac{15}{1.5}=10°$

For $\phi_D=10°$ and $i=45°$ from Fig. 4, $\frac{c}{F_TwH}=.108$

$$\frac{c}{F_TwH}=.108=\frac{c}{1.5\times64.3\times20};\ \text{whence } c=210\ \textit{lb. per sq. ft.}$$

(*b*) For the sudden drawdown case —

The weighted friction angle, $\phi_w = \frac{s-1}{s+e} \times \phi = \frac{1.8}{3.55} \times 15 = 7.6°$

$$\phi_D = \frac{\phi_w}{F_T} = \frac{7.6}{1.5} = 5.1°$$

From Fig. 4, for $\phi_D = 5.1°$ and $i = 45°$, $\frac{c}{F_T w H} = .136$

$$W_T = 64.3 + 62.5 = 126.8$$

$\frac{c}{F_T w H} = .136 = \frac{c}{1.5 \times 126.8 \times 20}$; whence $c =$ *520 lb. per sq. ft.*

The cohesion would be slightly lower than this value for a steady state of seepage.

(*c*) Complete consolidation will be assumed.

As in part (*a*), $\phi_D = 10°$

$\frac{c}{F_T w H} = .108 = \frac{c}{1.5 \times 126.8 \times 20}$; whence $c =$ *410 lb. per sq. ft.*

Previous to reaching complete consolidation the required value would be slightly higher.

(3) A railroad cut to a depth of 20 ft. must be made through a clay on which the value for cohesion corrected to allow for surface cracking is 400 lb./*SF*, $w = 115$ lb./*CF*, and $\phi = 10°$. A factor of safety of 1.75 is specified. It may be assumed that there will be no seepage. What is the allowable slope?

$$\phi_D = \frac{\phi}{F_T} = \frac{10}{1.75} = 5.7°$$

$$\frac{c}{F_T w H} = \frac{400}{1.75 \times 115 \times 20} = .099$$

From Fig. 4, when $\frac{c}{F_T w H} = .099$ and $\phi_D = 5.7°$, $i = 27°$

The allowable slope is thus about 2 to 1.

(4) A cut on a $1\frac{1}{4}:1$ slope is to be made in a clay on which tests show $c=680$ lb. per sq. ft. and $\phi=18°$. Unit weights are 64 lb. per cu. ft. submerged and 126 lb. per cu. ft. total. It is specified that a factor of safety with respect to cohesion of 2 is to be used. Seepage will occur during a part of each year. Surface cracking will occur, and it is estimated that this may invalidate the strength of 25 per cent of the rupture surface. What is the estimated allowable depth?

The available average cohesion becomes $.75\times680=510$ lb./SF

$$\cot i=1.25,\ i=39°;\ \phi_w=18\times\frac{64}{126}=9.1°$$

For $i=39°$ and $\phi=9.1°$, from Fig. 4, $\dfrac{c}{FwH}=.102$

$\dfrac{c}{FwH}=.102=\dfrac{510}{2\times126\times H}$; whence H, the allowable depth, is *20 feet.*

(5) A 40° slope is 30 feet in height. Tests on the soil give the following values: $c=350$ lb./SF, $w=110$ lb./CF, $\phi=20°$. The value for cohesion has been adjusted to allow for cracking at top of slope. It may be assumed that there will be no seepage. Determine —

(*a*) The factor of safety with respect to cohesion.

(*b*) The true factor of safety.

(*a*) For $\phi=20°$; $i=40°$; $\dfrac{c}{FwH}=.050$

$$\frac{c}{FwH}=.050=\frac{350}{F\times110\times30};\ \text{whence } F=2.1$$

(*b*) A direct solution is not possible, but a solution by trial is not difficult.

Using the test values for the soil and assuming any true factor of safety, the allowable height for a 40° slope may be figured. A few trials will indicate what factor of safety corresponds to the actual height of 30 ft.

Assuming $F_T=1.5$

$\phi_D=\dfrac{20}{1.5}=13.3°$ and from Fig. 4, for $\phi_D=13.3°$ and $i=40°$

$$\frac{c}{F_T w H} = .080 = \frac{350}{1.5 \times 110 \times H}\text{; whence } H = \mathit{26.5\ ft.}$$

Similar computations for F_T equal to 1.4 and 1.3 lead to —

F_T	H
1.5	26.5
1.4	30.3
1.3	35.0

And it is seen that for the actual height of 30 ft. $F_T = \mathit{1.4}$.

(6) A rolled fill dam is to be constructed using a material which has an inappreciable amount of very fine particles. For this material, tests show that $\phi = 35°$ and cohesion is inappreciable. A factor of safety of 1.5 is desired. What side slopes should be used?

Assuming no freeboard and sudden drawdown —

$$\phi_D = \frac{\phi}{F_T} = \frac{35}{1.5} = 23.3°$$

$\phi_w = \dfrac{s-1}{s+e}\phi_D$ = approx. $\dfrac{1}{2}\,\phi_D = \dfrac{1}{2} \times 23.3 = 11.7°$; whence $i = \mathit{11.7°}$, a slope of 1 on 5.

Assuming complete capillary saturation —

$$\phi_D = 23.3° \text{ as above}$$

and $i = 23.3°$, a slope of 1 on $2\frac{1}{3}$

This combination of high friction angle and flat slope leads to a large difference between the sudden drawdown and capillary saturation cases. The allowable slope depends on many factors which have not been mentioned, and the method of this paper can only bound it between the limits of 1 on $2\frac{1}{3}$ and 1 on 5. More detailed analyses which might be undertaken are a sudden drawdown analysis in which account is taken of the freeboard, or an analysis of the case of steady seepage using flow nets.

(7) A cut 30 ft. deep is to be made in a deposit of highly cohesive material which is 60 ft. deep and is underlaid by ledge. The shearing strength is essentially constant throughout the depth at 600 lb. per sq. ft. The unit weight is 120 lb. per cu. ft.

(*a*) For a factor of safety of 1.5, what side slopes are needed?

(*b*) What increased value of cohesion would be necessary for side slopes of 1.8 : 1?

$$(a)\ \text{For } \phi=0,\ D=\frac{60}{30}=2,\ \frac{c}{FwH}=\frac{600}{1.5\times120\times30}=.111$$

Fig. 8 gives $i=8°$, or a slope of 7 : 1

(*b*) $i=\cot^{-1} 1.8=29°$

For $D=2$ and $i=29°$, Fig. 8 gives $\frac{c}{FwH}=.171$

$$.171=\frac{c}{1.5\times120\times30};\quad \text{whence } c=920\ lb./SF$$

Fig. 8 also gives $n=0.8$, which means the rupture would break out at the surface 24 ft. from the toe. For a cut with a base width narrower than 24 ft., a somewhat lower cohesion would be required, but the absolute minimum would be for $n=0$, where

$$\frac{c}{FwH}=.154;\quad \text{whence } c=830\ lb./SF$$

Conclusion

By the use of the Stability Number, the solution of problems in stability of slopes becomes very simple. When the slope angle and the friction angle are known, this number may be obtained directly from Fig. 4, while for zero friction angle, if there is a limitation in the depth to which a rupture surface may extend, Fig. 8 will furnish the value. Nests of similar curves could be derived for more involved cross sections, such as those where the ground at the top of slope is not level, or where there is partial submergence, or for typical earth dam sections sloping in two directions. While such sections would apply to many actual problems, there is a question as to whether or not the large amount of work required for general solutions would be justified.

The dependability of the results of such solutions will depend entirely on the conditions. In a few ideal cases the results may be very dependable. More often there will be questionable items, such as the ever-present possibility of surface cracking at the top of the slope, which determine that the results can be accepted only as rough indications. If good judgment is used in estimating and attempting to evaluate the unknown factors, whatever the conditions may be, the results should be of value in arriving at logical conclusions.

The relative value of the different methods for solution of stability problems is largely one of academic interest. Accuracies far greater than those warranted have been adopted in this paper in an attempt to show that the two methods used to obtain the charts are at least as logical as any other methods available, and that they agree remarkably well with each other. The assumptions involved may be accepted as reasonable for any embankment which is essentially homogeneous and conforms approximately to the ideal cross section used, with a single exception. The assumption that cohesion is constant at all points may often vary considerably from the truth, and the use of the best average value that can be obtained is the only procedure available.

Although stability problems involve more questionable items than most engineering problems, it is seldom possible to make use of large factors of safety. Conditions are often such that about the largest factor of safety that may be chosen is 1.5, and sometimes a value this large may not be allowable.

Procedures for different conditions of saturation and seepage may be summarized as follows:

A. If the slope is continuously submerged, use the submerged unit weight. For partial submergence, the general solution is not applicable.

B. If the slope is submerged and values for cohesion and friction have been determined for this state, and if sudden drawdown is a possibility, use the total unit weight and the weighted friction angle.

C. For any embankment which is not submerged, through which there is seepage of water or any possibility of future seepage occurring, obtain the solutions for cases B and D. The solution for case C must fall between these two, and when they do not differ widely, as will often be the case, the results for case B may be used for C. Where B and D offer radically different requirements, no accurate answer is available by the method of this paper. However, it is to be hoped that future investigations of seepage cases by more involved methods will yield methods of approximate interpolation within the range between B and D.

D. For an intact cohesive soil, which is saturated or practically so, where the slope is dry and there is no possibility of future seepage of water, use the total unit weight and the friction angle as given by tests.

E. For a dried, fissured clay, this type of stability analysis does not apply.

Features which apply to all of the above items may be summarized as follows:

1. The depth to which surface cracks are likely to develop must be estimated or assumed. From this the percentage of arc which is not affected by cracking may be found. An average cohesion for use in computations may be obtained by multiplying this percentage by the unit cohesion as given by laboratory tests.

2. For slight variations of soil properties within the sliding mass, average values for cohesion, unit weight and friction angle may be used. For large variations the general solution is not strictly applicable, but in many cases, even where several distinctly different types of soil occur in a cross section, it has been found to give surprisingly good results. Thus it may at least be considered as a valuable check for complicated analyses.

The general type of solution which this paper presents may meet opposition by some engineers who feel that soil is too variable a material to be subjected to such analysis. However, such results in the hands of an experienced soil engineer, accompanied by data furnished by thorough investigations of the site and the soil involved, will give information which no responsible engineer can afford to overlook.

Acknowledgments

The writer wishes to acknowledge the advice and willing assistance of Dr. Glennon Gilboy in connection with the preparation of this paper. A large amount of valuable assistance was given by Mr. Harold A. Fidler of the Massachusetts Institute of Technology soil mechanics laboratory staff, who checked the mathematical derivations and performed a part of the computation work. To Professor Arthur Casagrande the writer wishes to express his thanks for reading the manuscript and for valuable suggestions.

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THE TREATMENT OF WOOL-SCOURING WASTE

By Robert Spurr Weston, Member*

(Presented at a meeting of the Sanitary Section of the Boston Society of Civil Engineers, held on April 7, 1937)

Wool-scouring waste results from the washing of wool in water with added soap, sodium carbonate and other detergents. Usually the wool is dusted before being scoured, and in this connection the freezing of the wool before dusting has been proposed and now is in use at two important New England mills. A paper (1)† regarding it was read before one of the affiliated societies in March, 1937.

In a few mills the grease in the wool is removed by a solvent, like naptha, after which the wool is scoured, using much less soap and alkali than when scoured in its raw state.

Wool as removed from the sheep's body contains much besides wool fiber, depending upon its kind and character. It may lose from 20 to 75 per cent of its weight in the scouring process. This loss includes the bodily excretions of the sheep, known as "yolk" (French, *suint*), which are partly soluble and partly insoluble in water. Wool also includes sheep manure, plant parts and geological samples of the lands inhabited by the producing sheep.

Grease wool — wool directly from the body of the sheep — shrinks the most in washing. To reduce freight and improve quality, some wools, particularly those from Australia, South Africa and the Argentine, are washed where grown. Such wools are called washed wools. Home-grown wool from the farms usually shrinks far less in scouring than do the wools from the ranges, domestic or foreign; the shrinkage may be as low as 20 to 25 per cent. "Pulled," "slipe," or "skin" wool, removed from the sheep's skin in the course of pulling or de-hairing for tanning or felting, contains some of the lime used in the pulling process. It is often low in grease.

Other animal hairs, like mohair, alpaca and camel's hair, are also scoured. While often dirty, their grease contents are low. Quantitatively, mohair is the most important of these.

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† Numbers in parentheses refer to Bibliography at end of paper.

The soluble matters in the wool include potash soaps which are combinations of oleic and other fatty acids. When the wool is washed, these soaps, and the added detergents, cause the emulsification of the wool grease. True wool grease does not form a soluble soap with alkali. Chemically, it is a wax rather than a fat. It consists of various esters of cholesterol and iso-cholesterol; cetyl; and carnaübyl and ceryl alcohol with oleic, lanopalmitic and other organic acids; also other compounds, like free cholesterol, in small proportions. In its refined state, wool grease is called lanolin (*Adeps lanæ*, U. S. P.), valuable for ointments, salves and emulsions.

Because this subject is being considered from the standpoint of stream pollution, the process of grease extraction from the wool by the use of naptha or other solvents will be discussed only briefly. In this

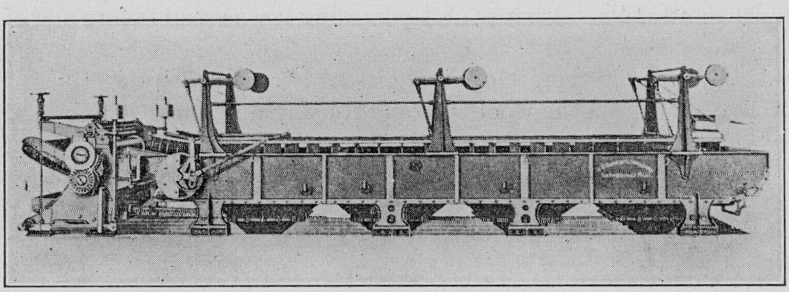


Fig. 1. — Typical Scouring Bowl

process, the dusted wool is treated with the solvent in closed extractors. This removes the grease and other soluble organic matter, leaving behind the dirt and débris which are afterwards removed by washing in water, with or without added detergents. The solvent is then recovered from the grease solution by distillation, the grease refined and marketed. The potash remains in the wool, and this process is therefore the most favorable one for the recovery of this substance from the scouring liquors, this because the interfering grease is removed before the wool is washed in water. Under favorable conditions it is practicable to evaporate and calcine the degreased liquor, and dissolve the potash from the ash.

Most wool combers object to extraction by solvents, saying that the process is too thorough, leaving the wool too harsh and requiring excessive re-oiling for carding and spinning. However, the process is being used in mills of the best grade.

Scouring

While, in small plants, vats with perforated false bottoms may be used for scouring wool, and the wool may be passed through the scouring liquors by hand, the process is usually carried out in trains of long bowls through which the wool is gently dragged by mechanically operated rakes or forks. Mills too small to use the modern bowls usually employ commission wool scourers.

The bowls are usually arranged in trains of four or five bowls. These may vary in width from 24 to 48 inches, and in length from 12 to 30 feet. Common arrangements of lengths of 48-inch bowls are as follows:

Length of Bowls (in Feet)

Process	Batch of 4 Bowls	Batch of 5 Bowls	Counter-Current	
			5 Bowls (A)	5 Bowls (B)
First bowl	30	21	16	16
Second bowl	24	27	16	27
Third bowl	18	21	27	24
Fourth bowl	18	16	27	24
Fifth bowl	–	14	21	24

There is a perforated screen in each bowl with settling compartment beneath, and above the screen the depth of liquor through which the wool is dragged is usually less than 12 inches. Pyramidal bottoms and drains are provided for dumping part or all of the contents of the bowls. Some bowls have auxiliary settling tanks alongside, with pumps for circulating the scouring liquor through them, thus keeping down the accumulation of grit and dirt.

A bowl known as the self-cleaning, or "Harrow," type is made in England. This bowl has a semicircular bottom with a screw conveyor along it. This conveyor has both right and left handed flights which carry the grit to a sump at the center of the bowl. The grit is discharged from this sump periodically through an automatic, quick-opening valve.

The sorted wool, previously dusted, is introduced at the near end of each bowl by a traveling apron, and is dragged slowly through the bowl by mechanical forks or rakes, and then passed through squeeze rolls at the far end, which rolls deliver it to the feeder of the next bowl, or, in the case of the last bowl, to the conveyor leading to the wool drier.

Most wools are easily scoured in an alkaline soap solution, but detergents, like tri-sodium phosphate or sodium silicate, and those containing creosols and other deodorants, are used in special cases. Sometimes, and usually in the counter-current process, no soap or alkali is added in the first bowl.

Temperatures are usually kept below 140° F. to avoid injury to the wool fiber. Common operating temperatures are 130° F. in the first,

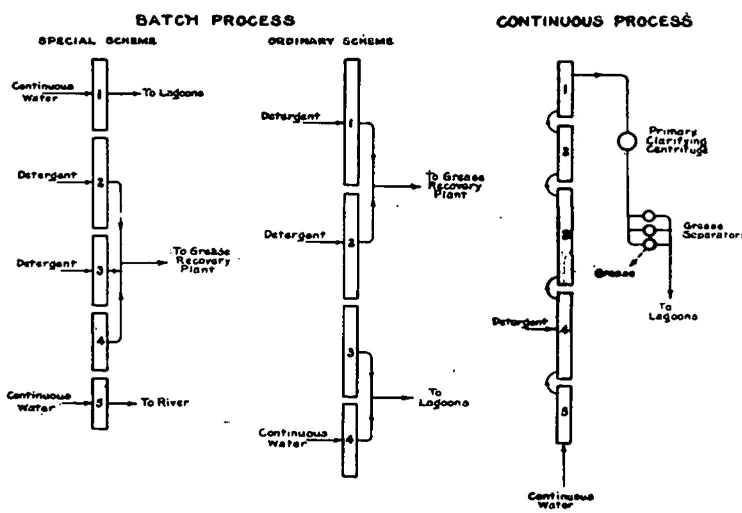


DIAGRAM SHOWING
VARIOUS METHODS OF SCOURING WOOL

FIG. 2

125° F. in the second, 120° F. in the third, and normal water temperatures in the rinsing bowl. Recording thermometers are in use in some mills, automatic temperature controllers also.

COUNTER-CURRENT SCOURING

In most wool-scouring plants the bowls are dumped singly or batchwise, although frequently the water from the last or last two bowls in the train is discharged continuously, even if the bowls are dumped periodically in addition. These bowls are used for rinsing the wool.

In cloth mills using wool of uniform grade the bowls may be partially or completely dumped after periods varying from four to twenty-four hours. Commission combing plants, however, may dump and refill bowls with each lot of wool. Carpet mills must make special provision for dirty wool. Therefore practices vary widely.

Batch dumping results in large consumption of water per pound of wool, very few mills using less than 1 gallon, and some more than 5 gallons, per pound of wool, as the following table, taken from the report of the Massachusetts State Board of Health to the Legislature, January 10, 1913, House Document No. 2150, illustrates:

WOOL SCOURED AND WASTE PRODUCED, BY MILLS IN LAWRENCE, MASSACHUSETTS, 1910

	Pounds per Day	First and Second Bowls		All Bowls	
		Gallons	Gallons per Pound	Gallons	Gallons per Pound
Lower Pacific	38,692	24,845	0.64	72,015	1.86
Washington	84,463	44,675	0.52	130,591	1.55
Kunhardt, G. E.	1,750	1,566	0.89	22,569	12.87
Lewis, E. Frank . . .	68,359	51,888	0.75	58,909	0.86
Ayer	38,460	32,108	0.83	35,877	0.93
Wood Worsted . . .	77,099	210,733	2.73	439,325	5.55
Average	–	–	1.06	–	2.15

An accurate study made by the Metropolitan District Water Supply Commission in 1935, at the Barre Wool Combing Company, a typical commission combing plant, and in co-operation with its engineers, showed an average of 1.99 gallons and a minimum of 1.6 gallons of water used per pound of wool.

A similar study made in 1936 at a typical high-grade worsted mill by the writer's firm showed an average use of 1.3 gallons in the first three bowls and of 2.0 gallons in the fourth bowl, a total of 3.3 gallons per pound of wool. At this plant the fourth bowl discharges continuously between customary six-hourly dumpings of all the bowls.

A large use of soap and alkali naturally follows a large consumption of water, for a sufficient concentration must be maintained regardless of the volume of water used. It is also a fact that a larger percentage of grease is recoverable from concentrated than from dilute waste, in either the centrifugal process or the acid-cracking process of recovery.

The above facts have led to the employment of the counter-current method, in so general use in chemical industry. When this is used, only the first bowl liquors are discharged, and these continuously at a slow rate, the loss being made up by pumping from the other bowls in the train in turn.

To use this method, the bowls, especially the first one or two in the train, should have bottoms with steep slopes, — 45° or more, — so that the drains may be opened and closed, frequently and quickly, to remove the sand and grit which accumulate during scouring, their removal being accomplished in this way with the minimal loss of liquid waste.

Modern scouring trains are so designed that the flow of water from the last bowl to the first is automatically controlled, yet subject to such changes in rate as the operator may elect.

Soap, alkali and other detergents are fed continuously, usually to the second or third bowl, thus maintaining constant conditions for scouring, saving from 20 to 40 per cent of the detergents used in the batch process, and reducing the consumption of water to much below one gallon, often below one half gallon per pound of wool.

The counter-current method is not only advantageous because the concentration of soap and alkali and other detergents can be maintained as desired and at the points desired, but also for grease recovery, because the heaviest of the interfering dirt is discharged to waste periodically, while the wool grease reaches a higher concentration when discharged from the first bowl only.

While the continuous process has been used in connection with the centrifugal process of grease recovery, it is equally advantageous in connection with the acid or any other method of treating the waste. It affects waste treatment because it reduces the volume of waste to be treated, and increases the yield of grease recovered.

The difference between the batch and continuous methods is illustrated by the accompanying flow sheet (Fig. 2).

Composition of Waste

Wool-scouring waste is grayish-brown in color, and, when fresh, possesses the characteristic odor of a sheepfold; when stale it ferments, turns dark, and gives off gases of decomposition, including hydrogen sulfide. Cyanogen compounds are sometimes formed, and when the wastes are treated with acid, these are evolved, sometimes in concentrations sufficient to overcome men who enter the treating tanks to clean them.

Typical results of analyses of samples of batch-process waste are given in the following tables. Counter-current wastes are two or three times as concentrated as the first bowl liquors from trains operating on the batch system.

TABLE I. — RESULTS OF ANALYSES OF TYPICAL WASTES

[Parts per million]

Determination	Kind of Waste: First Bowl, Bottoms (Plant A)	Combined Wastes (Plant A)	Average of 3 Bowls (Plant B, Texas Wool)	First Bowl (Plant B)	Second Bowl (Plant B)	Third Bowl (Plant B)	Fourth Bowl (Plant B)	First Bowl (Plant C)	Second Bowl (Plant C)	Third Bowl (Plant C)	Fourth Bowl (Plant C)	Integrated Discharge (Plant C)
Oxygen consumed:												
Total	8,950	7,900	–	15,400	6,200	3,400	1,500	–	–	210	205	230
Dissolved	2,150	3,900	–	–	–	–	–	–	–	–	–	–
Suspended	6,800	4,000	–	–	–	–	–	–	–	–	–	–
Total nitrogen	–	–	–	–	–	–	–	239	260	10.88	1.04	71.36
Alkalinity	2,955	3,125	15,200	15,000	9,400	3,000	900	18,000	11,000	500	75	550
Residue on evaporation:												
Total	68,540	25,475	56,620	72,490	21,710	6,050	1,350	117,440	71,160	2,020	420	1,960
Loss on ignition	20,950	17,915	30,090	40,900	9,850	3,440	725	91,680	61,260	1,480	320	1,530
Fixed mineral	47,590	7,560	26,530	31,590	11,860	2,610	625	25,760	9,900	540	100	430
Dissolved solids:												
Total	6,755	10,525	26,930	36,370	13,590	3,480	610	–	–	1,030	280	1,260
Loss on ignition	3,625	6,130	14,300	16,230	3,040	1,490	320	–	–	750	230	1,010
Fixed mineral	3,130	4,395	12,630	20,140	10,550	1,990	290	–	–	280	50	250
Suspended solids:												
Total	61,785	14,950	29,690	36,120	8,120	2,570	740	–	–	990	140	700
Loss on ignition	17,325	11,785	15,790	24,670	6,810	1,950	405	–	–	730	90	520
Fixed mineral	44,460	3,165	13,900	11,450	1,310	620	335	–	–	260	50	180
Settleable solids	55,350	4,846	–	8.40%*	2.80%*	0.90%*	1.10%*	–	–	–	–	–
Fats) (ether soluble)	8,945	10,500	–	–	–	–	–	–	–	–	–	–
Fats (acidified)	8,395	11,220	14,928	19,940	5,200	1,690	229	58,000	41,200	370	30	210
Oxygen demand (five days)	4,338	4,464	–	–	–	–	–	–	–	–	–	216

* Per cent by volume — twenty-four hours' subsidence.

TABLE I. — RESULTS OF ANALYSES OF TYPICAL WASTES — *Concluded*

[Parts per million]

Determination	Kind of Waste									
	Average, Plant D* (England)	Mixed, Plant E* (England)	Plant F, Carpet Mill, Yangtze Wool			From Report of Massachusetts Department of Public Health, 1930				Mill F
			First Bowl	Second Bowl	Third and Fourth Bowls	Mill A	Mill B	Mill C	Mill D	
Oxygen consumed:										
Total	318	1,106	–	–	–	5,747	3,136	9,383	2,950	26,100
Dissolved	–	–	–	–	–	–	–	–	–	–
Suspended	–	–	–	–	–	–	–	–	–	–
Total nitrogen	45	155	1,550	575	153	1,326	1,273	2,299	647	2,237
Alkalinity	1,039	3,031	12,300	4,200	720	–	–	–	–	–
Residue on evaporation:										
Total	3,196	14,122	119,000	43,000	5,400	95,542	69,070	217,903	39,147	114,112
Loss on ignition	1,897	8,712	–	–	–	73,310	40,190	78,613	24,520	72,448
Fixed mineral	1,299	5,410	–	–	–	22,232	28,880	139,290	14,627	41,664
Dissolved solids:										
Total	2,204	6,984	39,000	–	–	40,382	36,570	47,593	21,780	30,200
Loss on ignition	1,000	2,748	–	–	–	24,460	16,800	24,013	11,834	14,368
Fixed mineral	1,204	4,236	–	–	–	15,922	19,770	23,580	9,946	15,832
Suspended solids:										
Total	992	7,138	80,000	33,000	3,300	55,160	32,500	170,310	17,367	83,912
Loss on ignition	897	5,964	–	–	–	48,850	23,390	54,600	12,686	58,080
Fixed mineral	95	1,174	–	–	–	6,310	9,110	115,710	4,681	25,832
Settleable solids	–	–	27%†	15.5%†	2.45%†	–	–	–	–	–
Fats (ether soluble)	–	–	–	–	–	–	–	–	–	–
Fats (acidified)	1,392	7,140	10,450	1,900	450	51,350	20,090	41,500	16,560	44,175
Oxygen demand (five days)	–	–	–	–	–	–	–	–	–	–

* By Wilson & Calvert.

† Per cent by volume — twenty-four hours' subsidence.

Treatment of Waste

The two methods most often used for the treatment of waste and for grease recovery are known as the acid and the centrifugal process, respectively. They may be described as follows:

The Acid Process

The acid or acid-cracking process is old. It is mentioned in the third report of the British Rivers Pollution Commission of 1865, and has been in use for at least seventy-five years.

Briefly, it consists in adding sulfuric acid to the cooled wastes with stirring, and sometimes with the addition of silt, clay or other substances, to load or demulsify the dispersed grease. A low temperature is important for clarification. Properly treated waste usually has an acidity of from 0.1 to 0.2 per cent.

Successful treatment results in the precipitation of a large part — 85 to 90 per cent — of the grease as sludge. A scum containing some grease is also formed. After several hours of subsidence, the partially clarified liquor is decanted and the scum and sludge are treated for the recovery of grease.

Formerly the sludge or "magma" was dried on covered beds of cinders or sand, usually covered in turn with a layer of sawdust to promote filtration and drying. In England they are called "magma" beds. When dry enough to handle with a spade, portions of sludge about one foot square were wrapped in bagging forming so-called "puddings." These latter were then stacked in layers between steel plates in a steam jacketed hydraulic press, and the grease tried out with heat and pressure.

The labor involved in this method of grease extraction was costly, and in recent years most of the hydraulic presses have been superseded by filter presses, the heated wet sludge being forced through the steam-heated presses. For handling the sludge, sometimes heated steel ejector tanks employing compressed air (monte-jus), sometimes special sludge pumps and automatic heaters with steam coils, are used.

From the presses there drains a mixture of grease and water which is passed to a separating tank. The grease is then separated by gravity, refined by washing, heat and hot storage, and marketed. The sludge from the presses, like the "puddings" also, is disposed of by dumping. It is of little or no value, except for the grease left in it, sometimes recovered by extraction with a solvent.

Under ordinary conditions, the acid process will remove from 80 to 90 per cent of the grease, but there are wastes from certain wools which are difficult to treat. Some of these contain proteins which overcome the demulsifying effect of the acid. Others, like those from wools produced in the area affected by the 1935 dust storms, contain suspended matter so fine and light that subsidence of the coagulated grease is limited. The suspended matter with its load of grease is not quite low enough in specific gravity to be carried to the surface with the scum, nor heavy enough to precipitate; consequently it is decanted with the

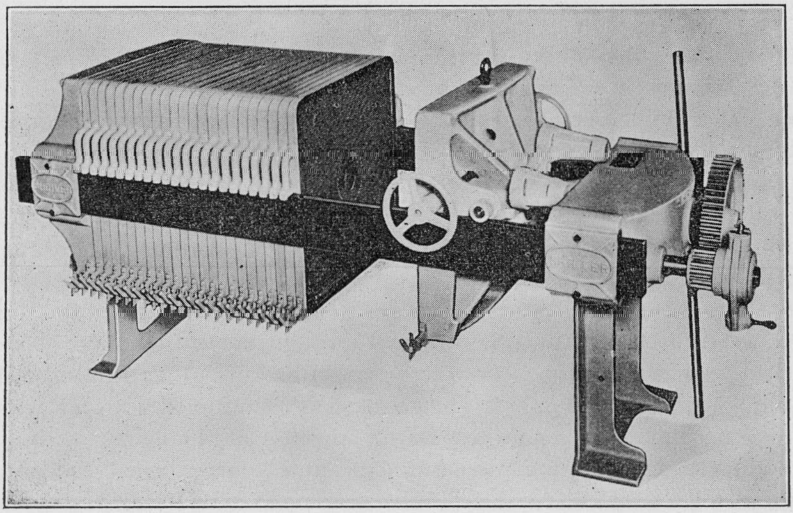


FIG. 3. — TYPICAL FILTER PRESS, CLOTHS NOT SHOWN

partially clarified liquor and lost. In some cases acid treatment removes only 70 per cent of the grease.

These and other difficult wastes call for special treatment. Sometimes the addition of silt, clay or other decolloiders or absorbents will effect clarification. Pretreatment with lime and chlorine has been suggested by de Raeve (2). However, each waste presents its own problem, and no specific general treatment will apply to all.

The counter-current scouring is of especial service in connection with acid treatment. It greatly reduces the volume of waste so that cooling and decantation become unnecessary and the whole contents of the cracking tanks may be passed through the filter presses, thus saving heat and storage, and increasing the yield of grease.

The yield of grease from certain wastes by acid treatment and hot pressing is low, much grease being left in the press cake and lost. This loss is due to the high melting points of certain fats and waxes, and the difficulty of extracting them with hot water. Generally, from 10 to 30 per cent, sometimes more, of grease is contained in the cake. In some cases, particularly in England, press cake containing much grease is extracted with naptha for the further recovery of the grease. The process will be referred to again under "Secondary Treatment."

Centrifugal Process

For about twenty-five years, centrifugal machines similar to those used for separating cream from milk, or for purifying lubricating oil in power plants, have been used to separate wool grease from wool-scouring waste, first freed from the grosser settleable solids by subsidence in tanks, or by primary centrifugalization. During the World War, when the price of centrifugal grease was high, many mills installed these machines, in some cases replacing the acid-cracking processes to introduce them.

In this process, the wastes, first treated to remove settleable solids, were heated to 160° F., and then passed through the centrifugals. These removed from 40 to 60 per cent of the contained grease and most of the remaining suspended matter. The grease was then mixed with hot water and re-centrifugalized, while the watery portion of the waste, with soluble soaps and remaining grease and organic matter, was discharged untreated.

A detailed description of a plant of this type, that of the Hudson Worsted Company, was presented to this Society by Mr. George G. Bogren in 1926 (3).

Two makes of machines, the Sharples and the De Laval, are most commonly used; the former has a bowl 30 inches long and 4.5 inches in diameter, without internal parts, and operating at around 15,000 revolutions per minute; the latter has a bowl about 12 inches deep by 20 inches in diameter, filled with conical discs and operating at around 6,000 revolutions per minute. The discs in the latter machine, by diminishing the thickness of liquid in which centrifugal separation takes place, permit a lower speed; the former machine depends upon its high speed, developing a force 13,500 times that of gravity. Each machine has its advantages.

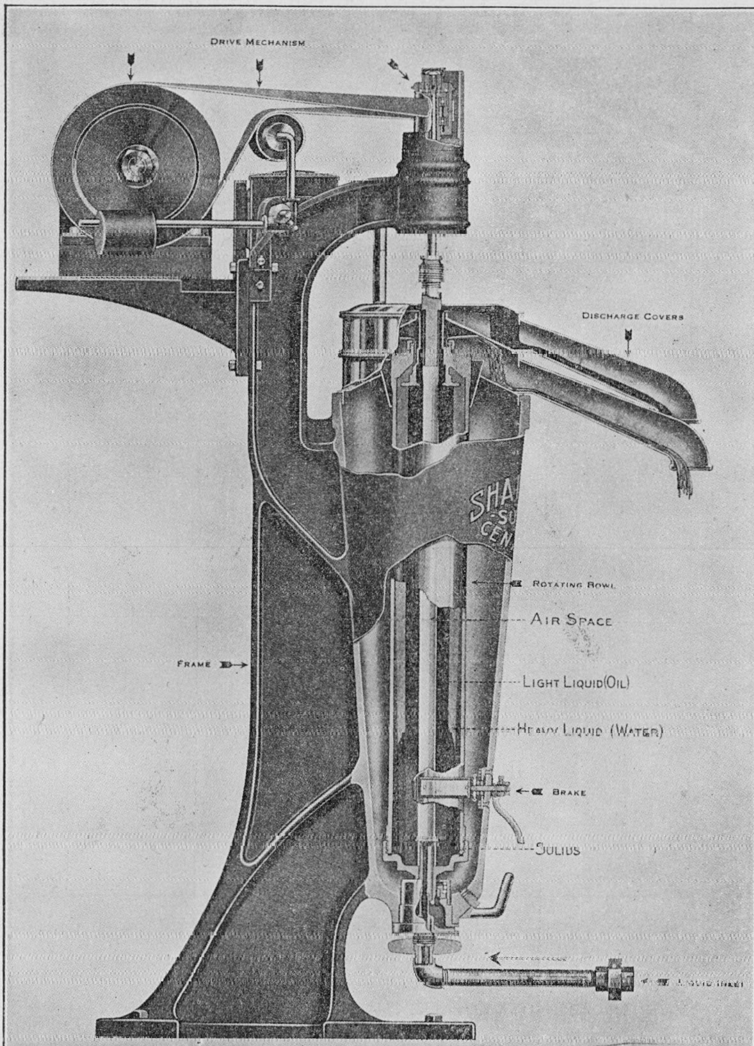


FIG. 4. — SECTIONAL FLOW VIEW OF SHARPLES SUPER CENTRIFUGE

The grease discharged from the primary machine is refined by washing and re-running through a centrifuge, and by storage with heat to dehydrate the grease. It is then barreled and marketed.

In the course of operation, considerable dirt accumulates in the bowls of the machine, making periodic cleaning necessary.

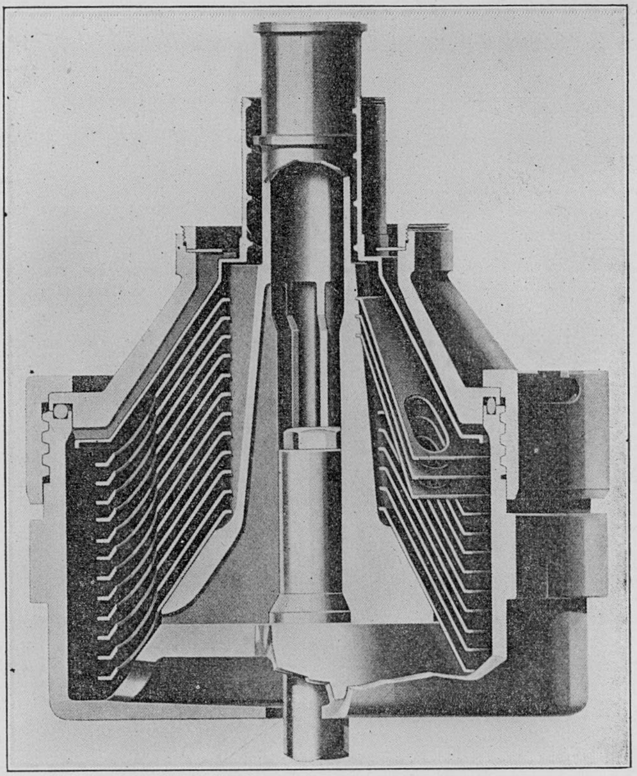


Fig. 5.—Cross-Sectional View of De Laval Purifier Bowl

Effective Preliminary Treatment

The use of subsiding tanks is not the best way to remove settleable solids. Much grease is thus entrained with the sediment and lost, while long storage introduces fermentation which gives the recovered grease a bad odor and high color, consequently lowering its selling price.

To avoid subsidence in basins, primary or clarifying centrifuges have come into use. The one most commonly used is an ordinary vertical centrifugal machine with an imperforate basket varying in diameter from 32 to 48 inches. The dirt and grit which accumulate on the inside of the basket are removed periodically, and while manufacturers have devised mechanical unloaders for this type of machine, the cleaning of the baskets by hand is usually practiced.

Operators usually object to cleaning the vertical machines by hand unless artificially ventilated on account of the steam and odor given off. So far, mechanical unloaders, while useful for some materials, have

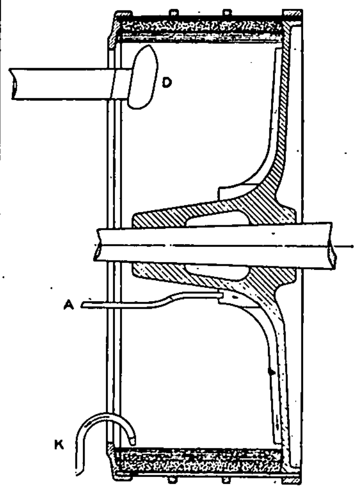


Diagram of the Decanter Basket. A, feed; D, cutter; K, skimming tube.

FIG. 6. — CROSS SECTION OF HORIZONTAL CENTRIFUGAL CLARIFIER

not been entirely successful for cleaning these machines when handling wool-scouring waste.

To overcome hand cleaning, and for greater economy of operation, automatically cleaned horizontal machines have been devised. The ones most generally used are of European manufacture. One of these is sold by the Sharples Specialty Company. These horizontal machines have baskets of two diameters, 48 and 63 inches, with widths of 22.5

and 23 inches, and operate at rates of 750 and 500 gallons per minute, respectively.

In operating a horizontal centrifuge, the warm waste liquors are passed into the basket, the removable solids collecting on the wall and forming a cake. When the cake has reached its maximal depth, the inflow is stopped; then a skimming tube (K, Fig. 6) is used to remove the clarified liquor, after which the cake is removed by a pointed cutter (D) which traverses it like a lathe tool. The solids fall into a hopper, and from this into a chute which delivers them to a bin or conveyor convenient for disposal. Owing to the short operating cycle, one of these machines, while costly, will do more work than two vertical machines cleaned by hand.

Lanolin

While ordinary wool grease contains lanolin, it may also contain other fats or fatty acids. Lanolin itself has a high melting point (38 to 40° C.), and if other fats, like olive oil, for example, be present, it is difficult to prepare U. S. P. lanolin from wool grease. It is for this reason that the problem of waste disposal is rarely linked with the manufacture of lanolin.

Lanolin is made from either centrifugal grease, or that extracted by benzine, naptha, or an non-inflammable solvent like trichlorethylene, from the sludge in the acid process (4), or from filter press cake. It is necessary to remove foreign fatty acids by treatment with lime, and recover the lanolin by extraction with alcohol, a process usually too complicated for practice in works designed primarily to reduce stream pollution, or to recover grease at a profit.

If solvents may be used to extract grease, one naturally asks why not treat the waste with acid, recover the cold sludge by filter presses, and extract it with naptha? Unfortunately, the sludge contains too much grease of high melting point, and filter cloths clog too rapidly to permit filtration at low temperatures.

It is possible that the so-called "Precoat" vacuum filter, with its coating of applied diatomaceous earth ("Filter-cote"), might dry the cold sludge sufficiently to permit its subsequent extraction with solvents, but realization is not yet.

Disposal by Dilution

It is easy to understand that an acid plant with a daily discharge of say 50,000 gallons of waste, containing 0.15 per cent of acid, would require 630 pounds of alkalinity in the stream into which it was discharged. The alkalinity of most New England streams is so low that a discharge of flow of from 5 to 15 million gallons per day might be required to neutralize the acid from this volume of acid effluent. This discharge is well below that of many mill streams. Again, the bio-chemical oxygen demand of the acid effluent, say 2,500 parts per million, or 18,400 pounds per million gallons, obviously requires a stream flow of about 11 million gallons per day for 50,000 gallons of effluent when the water contains 10 parts per million, or 83.4 pounds of oxygen per million gallons, — this without allowance for re-aeration.

Likewise, the effluent from the centrifugal process requires a high degree of dilution to prevent nuisance. At Hudson, on the Assabet River, which sometimes has a dry weather discharge of less than 6 million gallons per day, it has been found necessary to store the effluent from the centrifugal machines during the drier third of the year. These machines treat the discharges of the first and second bowls only, the third and fourth bowls discharging into the stream most of the time, into the lagoons during the driest weeks. The lagoons in which the waste is stored during the drier third of the year are emptied during the periods of high water. The five-day bio-chemical oxygen demand of waste from the first and second bowls, whose discharge amounts to 35,000 gallons a day, requires a stream discharge of about 17,000,000 gallons a day for disposal in water containing 10 parts per million of oxygen with no allowance for re-aeration.

This plant has an interesting history. Before 1909 the waste was discharged into the city sewer, but the grease clogged the sewage beds. Then acid cracking was employed, the filtered sewage effluent being discharged into the Assabet River. Then odors caused the neighbors to go to court and obtain their abatement. Then, in 1916, the centrifugal process was introduced, and the plant enlarged. Then a downstream mill owner complained. A temporary filter was built at a downstream mill for its benefit, and later on lagoons for storage of the effluent during dry weather were constructed.

In 1918, an evaporator was bought to recover potash from the centrifugal effluent, but the Armistice came first, and the apparatus was never unpacked.

Sludge presses, like the "Berrigan" and the ordinary plate press, were being tried with acid sludge, but the equity suits threw them out of consideration. Later, a vertical, solid-bowl centrifugal was purchased to supplement the settling tanks, but the operators objected to the steam and odor. The centrifugal was shut down and additional settling tanks were built.

At the present time this plant is being enlarged, and the new train of bowls, the fourth in service, and possibly others, will be operated on the counter-current plan. This plan should make enlargement of the grease plant unnecessary. However, for better efficiency and economy, settling tanks will be replaced by a horizontal, self-cleaning centrifugal clarifier.

SECONDARY TREATMENT

The recovery of grease can usually be carried on for less than the cost of operation, exclusive of fixed charges, and in some cases the latter may be earned in part or in whole. However, the degreased effluents, whether from the acid or from the centrifugal process, still have large capacities for polluting streams. This may be realized when one considers the acid character (0.1 to 0.2 per cent) of the effluent from the cracking process, removing less than 90 per cent of the grease, or the organic content of the effluent from the centrifugal process, generally removing less than 65 per cent of the grease, often less than 50 per cent.

In England, acid effluents have been treated with lime to neutralize them, and with a further dose of lime with ferric sulfate to coagulate and precipitate their suspended matter. The liquors so treated clarify readily, the sludge settling out in less than four hours, the supernatant liquor being clear, straw-colored, and having a five-day bio-chemical oxygen demand of less than 300 parts per million, which is low enough for discharge into most industrial streams with impunity. If required, however, the clear effluent may be further treated on bio-filters at high rates.

In this treatment by chemical precipitation, the problem of disposing of the bulky sludge, whose volume may be one fifth of that of the treated liquor, still remains. Drying in covered sludge beds is a possibility, and has been practiced in England, but the most attractive method is to use the vacuum filter. This device has the advantage of delivering a fairly dry cake convenient for hauling away, therefore more attractive to those who might use it for a fertilizer than if shoveling the dried sludge from a sand bed were a prerequisite.

In England (5) secondary treatment of the acid wastes has been carried out by filtration, double filters being used most often. The primary filter is of cinders with a layer of sawdust on top, the sawdust being scraped off and renewed frequently. Such a filter was in use at Hudson twenty-four years ago.

The secondary filter is an ordinary intermittent filter. It does most of the oxidizing; the primary filter apparently acts to restart bacterial decomposition of the waste, which it receives after treatment with heat and chemicals which tend to destroy the fermenting bacteria.

Early experience at Hudson, Massachusetts, showed the limitations of intermittent sand filters when an excessive amount of wool-scouring waste was discharged into the municipal sewers and passed to the beds.

In 1895 the Massachusetts State Board of Health began its experiments with wool-scouring waste, and an account of these by Clark (6) appeared in the report of 1895.

These resulted in failure when wool liquor alone was applied to filters, and success only when greatly diluted with domestic sewage. When clarified with various chemicals, the liquor could be applied to coke filters, but practically no additional purification was obtained, evidently because biological action could not be set up during the short period of passage through the filters.

In 1933 the writer's firm studied the problem of the treatment of the waste from a carpet mill in Saxonville, on the Sudbury River. The daily waste from this mill — 7,500 gallons discharged batchwise — had caused serious pollution, especially at a swimming hole in the river below.

This mill scoured coarse, dirty wool, the discharged waste, sometimes containing 15 per cent of sediment by volume. The total residue on evaporation of the liquor averaged 4.17 per cent. On the other hand, the fats were low, — 0.5 per cent.

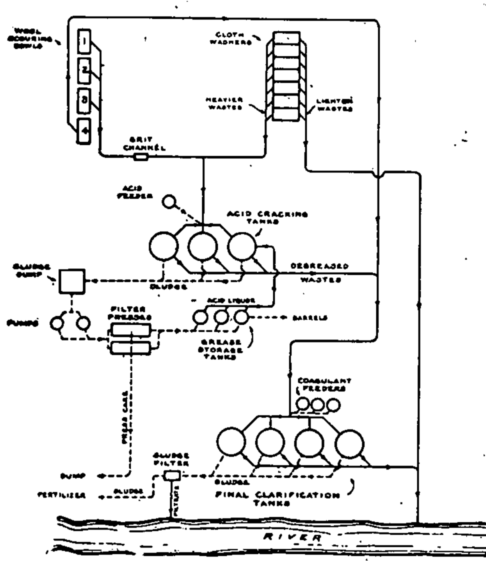
For the treatment of this waste plain subsidence was advised, and permission was asked to discharge the settled waste into the Framingham sewer during the drier half of the year. The town, fearing damage to its works, asked the advice of the State Department of Health. Experiments at Lawrence followed accordingly.

The experiments showed that 1 per cent of settled wool-scouring waste in the town sewer would not seriously affect either a sand filter operated at a rate of 0.42, or a trickling filter at a rate of 1.5 million gallons per acre per day, and following them the Department recommended that, subsequent to the construction of the proposed trickling filters, the equalized discharge of settled wastes be received in the Framingham system during the months of June to November, inclusive.

A plant is now being built at a mill in Rhode Island for the separate treatment of wool-scouring and cloth-washing wastes. This mill scours 1,000 pounds of wool per hour for twenty-two hours a day, and in addition washes much cloth. The discharge of these wastes into a stream, which has a discharge of only 2.49 million gallons per day for the driest 20 per cent of the time, produces a nuisance, the abatement of which is now being worked for.

Owing to the insufficiency of either the acid or the centrifugal process, it was decided to treat the stronger wastes, both from the scouring bowls and the cloth washers, by the acid process, mix the acid effluent with the rinse water from the fourth bowl, and treat the mixture with lime and ferric chloride in subsiding tanks, with stirring. It was found that only the run-off for the first five to seven minutes from the cloth washers needed to be treated.

The following flow diagram illustrates the methods of treating these wastes:



FLOW DIAGRAM FOR
WOOLEN MILL WASTES DISPOSAL
WITH SECONDARY TREATMENT

FIG. 7

The cloth-washing wastes and wool-scouring wastes are pumped to cracking tanks where they are allowed to cool. Acid is then added with stirring, and, after subsidence, the acid effluent is decanted, while the sludge is treated by hot pressing, followed by separation and refining of the grease in the usual way.

The decanted effluent is then pumped to the secondary tanks together with rinse water from the fourth bowl. Ferric chloride and lime are then applied, the sludge subsides rapidly, and the clear alkaline effluent is discharged into the river.

The sludge is to be dried out on a vacuum filter. It has a fertilizer value of about $1.50 a ton, which it is hoped is enough to get it hauled away at no cost to the works. This sludge will contain about 72 per cent of moisture and may be handled easily in comparison with the sludge from ordinary drying beds.

The plant will have a capacity for handling 29,000 gallons of wool-scouring waste, and 52,500 gallons of cloth-washing waste in twenty-four hours in the primary or acid-cracking tanks, and 125,000 gallons per day of mixed acid effluent and fourth bowl liquor in the secondary tanks. About 280,000 gallons per day of rinsing water and other wastes may be discharged untreated with impunity. Under ordinary conditions, 47 per cent of the total waste from the mill can be treated; under maximal conditions, about 30 per cent. During the drier months of the year, treatment must reduce the oxygen demand by 75 per cent.

While most of the plant is approaching completion, the vacuum filter has not yet been delivered. When tests were made for a preliminary plan, the mill was scouring Texas wool. Tests with a small laboratory filter showed that the sludge from 135,000 gallons per day of waste could be handled on a vacuum filter having 130 square feet of surface. Later on, with the mill scouring a high grade of wool from the region of the dust storms, it was found that on account of the presence of fine suspended matter, coagulation by acid was ineffective. A small filter was then brought on from the filter company's laboratory, when tests showed that only the "Precoat" filter, having an area of 200 square feet, could do the work, and that not very well. The cracking process removed only about 70 per cent of the fat in the mixed waste, leaving too much in the secondary sludge for effective operation of the vacuum filter.

Then special treatment was devised for the cracking process, and a higher degree of removal of grease was obtained. Then a barrel of sludge was sent to the filter company's laboratory, when it was found that the regular filter would work even better than the "Precoat" filter. However, 150 square feet of surface were found to be necessary, as compared with 130 square feet, the first estimate.

After consideration it was decided to delay ordering the filter until after the cracking plant was in operation, when the experimental filter will be brought to the plant and tests made with various types of waste, meanwhile partially neutralizing the primary effluent with lime to prevent acid conditions in the river.

In the event of failure, which is not looked for, because of the successful modification of the cracking process, covered drying beds will be indicated at 50 per cent increase in construction cost. While this higher cost might be offset by higher operating costs of the filter, it is expected that the possibility of disposing of the better-dried sludge, in

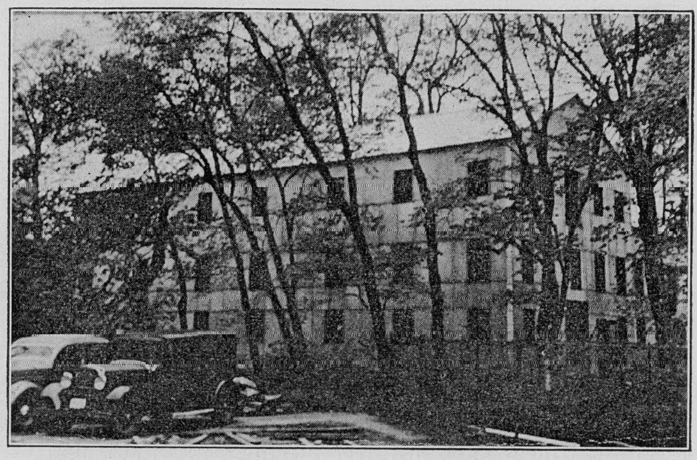


Fig. 8. — Peace Dale Works

addition to the greater convenience of operation and freedom from odor nuisance, will make the vacuum filter preferable by far.

Should this mill adopt the counter-current method of scouring, still better performance would be expected.

The accompanying tables show the results of the subsidence and treatment of wastes:

TABLE II. — RESULTS OF ANALYSES OF EFFLUENTS

[Parts per million]

DETERMINATION	Acid Effluent (Low Grade)	Acid Effluent (England)	Acid Effluent (Plant A)	Acid Effluent, Filtered (Plant H)	Secondary Effluent (Plant B)	Secondary Effluent, Filtered (England)	Centrifugal Effluent (Plant E)	Primary Clarifier Effluent (Plant E)
Total nitrogen	–	127	73	–	–	20	2,237	2,237
Oxygen consumed	3,140	674	2,255	873	–	114	24,300	24,700
Alkalinity	220	–	–	–	515	–	11,200	11,700
Acidity	–	–	1,320	1,300	–	–	–	–
Residue on evaporation:								
Total	22,005	13,902	11,230	14,306	11,526	11,671	79,640	93,704
Suspended	2,391	102	1,410	82	146	63	50,008	56,544
Dissolved	19,614	13,800	4,975	14,224	11,380	11,608	29,632	39,160
Mineral residue:								
Total	16,205	10,152	6,255	–	10,170	10,020	28,820	27,336
Suspended	321	22	70	–	82	29	11,380	8,792
Dissolved	15,884	10,130	1,340	–	10,088	9,991	17,440	18,544
Loss on ignition:								
Total	6,800	3,750	4,975	–	1,356	1,651	50,820	66,368
Suspended	2,071	80	1,340	–	64	34	38,628	45,752
Dissolved	3,730	3,670	3,635	–	1,292	1,617	12,192	20,616
Fats (ether soluble)	–	98	1,535	200	–	–	22,730	44,842
Oxygen demand — 5 days	–	–	–	–	163	Trace	–	–

TABLE III. — TYPICAL RESULTS OF ANALYSES OF SLUDGES AND PRESS CAKES

[Parts per million]

DETERMINATION	Moist Sludge (England)	Press Cake (England)	Acid Cake (Plant H)	Acid Sludge (Plant B)	Secondary Sludge (Plant B)
Moisture	57.91	21.98	9.10	82.05	72
Organic and volatile matter	39.43	67.05	–	9.73	14.3
Ash	2.66	10.97	–	8.22	13.7
	100.00	100.00	–	100.00	100.0
Dry Basis					
Organic and volatile matter	93.69	85.94	–	52.4	51.2
Ash	6.31	14.06	–	45.8	48.8
Total nitrogen	1.65	4.55	–	–	–
Fat	76.69	32.39	40.61	5.1	3.0

OTHER METHODS

The cake from either the filter press or the vacuum filter may contain as much as 40 per cent of fat. Where economical, this may be extracted by a solvent like naptha, and the latter recovered by distillation. However, the process introduces a fire hazard, even when conducted in an atmosphere of carbon dioxide, and the writer knows of no mill in this country which uses it, although its use abroad has been reported. However, some of the new non-inflammable solvents, like trichlorethylene, give new hopes.

Evaporation as a preliminary to treatment in centrifugal machines, followed by incineration of the effluent for the recovery of potash, was suggested in the report of the British Commission in 1868. It was tried out in a mill in Bradford and given up because of difficulties due to varying grades of wool.

Most of the advantages of evaporation may be obtained by the use of the counter-current method, which permits either acid treatment without decantation, or centrifugal treatment with increased yields.

In England, the West Riding of Yorkshire Rivers Board (7) found that acid-cracking effluents neutralized as planned for the plant described above are amenable to further treatment on trickling filters at rates varying from 30 to 42 gallons per cubic yard. They also found that these liquors, after a considerable dilution, may be successfully treated by the activated sludge process.

The author wishes to thank Mr. George G. Bogren for assistance in the preparation of the tables and illustrations for this paper, and to thank various mills for the use of certain information contained herein.

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EXPERIENCES AT LOUISVILLE, KENTUCKY, DURING THE OHIO RIVER FLOOD OF 1937

By E. Sherman Chase, Member*

(Presented at a meeting of the Sanitary Section of the Boston Society of Civil Engineers, held on March 3, 1937)

It is difficult to measure the relative magnitude of major disasters inasmuch as there are several yardsticks which might be applied, such as numbers of people affected, loss of property and loss of life. However, there is no question but that the recent Ohio River flood ranks as one of the greatest peace-time disasters of this country as measured by numbers of people affected and by loss of property and wages, although, fortunately, not by loss of life.

General Description of Flood and Conditions resulting Therefrom

Description of Flood Conditions

My own observations with respect to the flood are confined mainly to conditions at and around Louisville and to the Ohio River Valley as viewed from an airplane between Cincinnati and Louisville.

The cause of the flood was a long-continued heavy rainfall over a large proportion of the Ohio River drainage area at a time when ground conditions were such as to produce a high run-off ratio. During January, 1937, Louisville, for example, had 19.17 inches of precipitation, nearly five times normal for the month. Of this rainfall 17.38 inches occurred during the sixteen-day period from January 9 to 24, inclusive, or an average during this period of more than 1 inch per day. These conditions with respect to rainfall appear to have been typical over most of the watershed.

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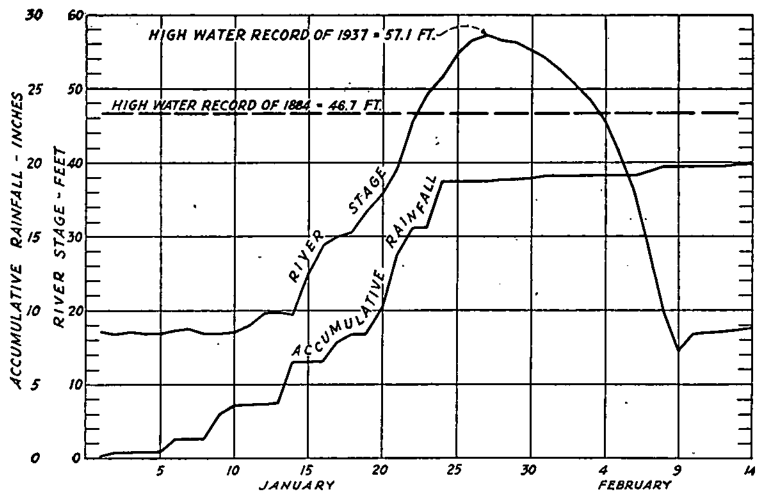
At Louisville the first sharp rise in river stage occurred on the 15th of January. The river continued to rise at a rapid rate from this date until the 27th of the month, when a stage of 57.1 feet was reached, constituting the highest record known. The previous high-water record occurred on February 18, 1884, when the river reached the stage of 46.7. This 1884 record was reached on the 23d of January of the present



RIVER STAGES AND ACCUMULATIVE RAINFALL AT LOUISVILLE, KENTUCKY - 1937

FIG. 1

year, and was exceeded for the remainder of the month and for four days in February, a period of twelve consecutive days. The estimated quantity of water flowing at Louisville at the time of the maximum stage was 1,180,000 second feet, equivalent to the entire contents of the Wachusett Reservoir, passing Louisville every two hours.

The Weather Bureau records of rainfall and river stage at Louisville for January and February, 1937, are given in Table 1:

TABLE 1. — RAINFALL AND RIVER STAGE AT LOUISVILLE, KENTUCKY

Day	January Rainfall (Inches)	January River Stage (Feet)	February Rainfall (Inches)	February River Stage (Feet)
1	.07	17.1	.00	52.6
2	.31	16.7	.00	50.6
3	.00	17.0	.00	48.5
4	.00	16.7	T	45.5
5	.00	16.7	.00	41.4
6	.95	17.1	T	36.0
7	.05	17.3	.23	28.8
8	T	16.9	.25	19.7
9	1.62	16.9	.00	14.5
10	.70	17.0	T	16.8
11	T	17.9	.00	16.9
12	T	19.5	.00	17.0
13	.09	19.9	.20	17.1
14	2.71	19.5	.00	17.5
15	.02	24.9	.07	17.0
16	.00	29.0	.03	17.1
17	1.46	30.0	.00	16.8
18	.47	30.8	.14	17.0
19	T	33.5	.03	17.0
20	1.70	35.9	.18	17.2
21	3.68	39.1	T	17.0
22	1.76	45.4	.05	17.0
23	.06	49.4	.09	16.9
24	3.11	51.5	.00	16.8
25	.00	54.8	T	17.0
26	.00	56.6	T	17.0
27	.00	57.1	.31	17.1
28	.18	56.8	.07	17.0
29	.00	56.4	–	–
30	.05	55.4	–	–
31	.18	54.1	–	–
Total	19.17	–	1.65	–
Normal	4.00	–	3.55	–

As a result of the elevation to which the river rose, the main business and industrial areas of Louisville, with the exception of a narrow strip perhaps a mile long and two or three blocks wide, were completely flooded. In addition, substantial residential areas were under water, particularly in the so-called West End of Louisville. In all, possibly 75 per cent of the developed area of Louisville was inundated.

Outside the city limits about 50 square miles of the County of Jefferson were under water, largely the area extending southerly along the east

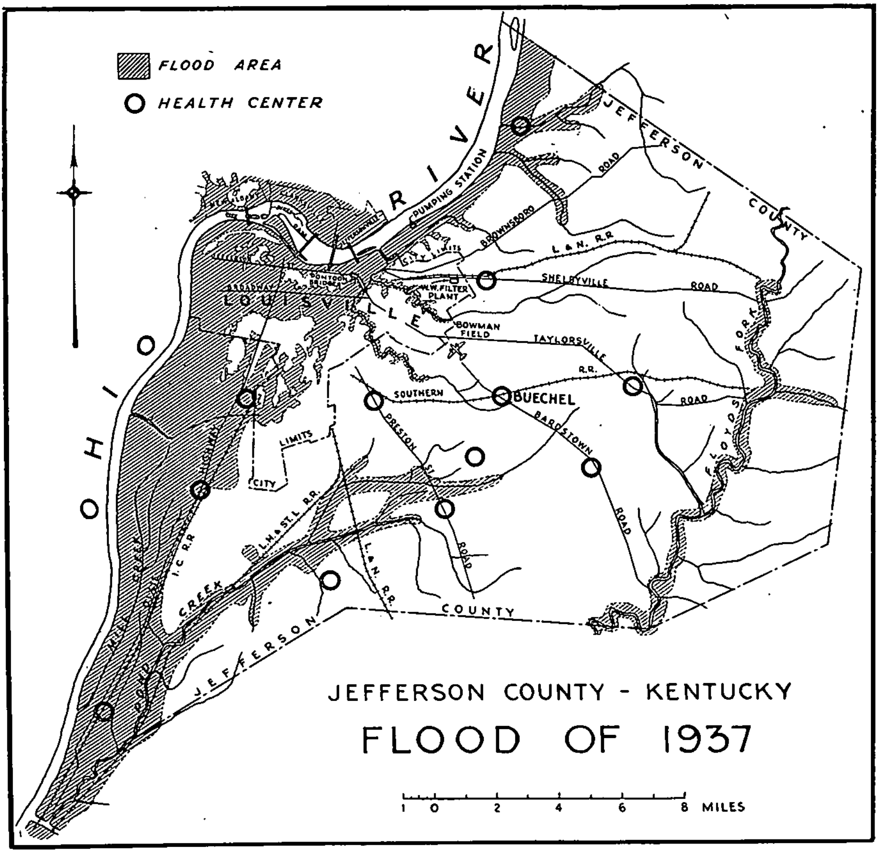


FIG. 2

bank of the Ohio River west of the Dixie Highway out of Louisville. Backwater from the Ohio extended into the county along the valleys of small tributaries, and while such backwaters resulted in the flooding of relatively small areas, they did flood highways to such an extent as to materially hinder transportation through the county.

General Conditions in Louisville

My own observations of conditions at Louisville began on the morning of January 28, the day after the flood had reached its peak. The waters had just begun to recede, although the recession was negligible, consequently physical conditions with respect to flooding were practically at their very worst.

The central part of Louisville, which had not been flooded and in which are located the city hall, court house and some of the hotels, could be reached only by boats or by a somewhat precarious pontoon bridge made of planks and whiskey barrels.

Evacuation of flooded areas in the city had begun the previous Saturday, but did not reach substantial proportions until Sunday and Monday. Some refugees fled from the cities along the radial highways leading to the south and southeast, others were housed in the armory and other public buildings within the city, in factories, private houses and hospitals. Others were transported by train to the interiors of Kentucky and adjacent States. About 75,000 refugees were cleared through the armory and 150,000 through the county.

At the time of my arrival there were many refugees in the armory, and evacuation from the central part of the city by boats and the pontoon bridge was still proceeding. Long lines of negroes were waiting to obtain food and other supplies at a number of relief stations within this central area. Broadway, one of the principal streets through the commercial part of Louisville, was under water with motorboats plying up and down the street for practically its entire length of five and one half miles.

There was no electrical service and consequently no electric lights and no power for the operation of electrical equipment. The low lift pumping station of the public water supply was partly under water, and steam for the operation of the pumps was being obtained from a steamboat moored adjacent to the pumping station. Due to temporary failure of pumping equipment before the emergency steam plant was available, the water in storage had been greatly depleted and water was being rationed to the city a few hours at a time. Telephone service was functioning at least to some extent, although the traffic was greatly congested. The natural gas supply apparently had not been materially impaired. Railroad service into Louisville was practically at a standstill, as all stations in the city were under water. Buildings with flooded basements which were still occupied were without heat. All business was suspended, and those not refugees were taking care of refugees or were busy with other tasks resulting from the disaster.

The relief activities might be divided roughly into the following main items:

1. Evacuation and transportation.
2. Housing, clothing and feeding.
3. Medical and health supervision.
4. Policing and quarantine.

It is impossible to describe, with any degree of accuracy, how the several relief activities were organized. Apparently the majority of those engaged in this work were volunteers who found, largely of their own accord, the niches into which they best fitted. Naturally there was a good deal of confusion and lost motion. There was a mayor's relief committee headed by Mayor Neville Miller. The American Legion did excellent work in matters relating to evacuation, transportation and supplies. The National Guard and the police force of Louisville and police officers from other States and cities maintained close control of traffic and assisted in relief work and in the protection of property. State, county and city health departments and the United States Public Health Service were actively engaged in matters relating to typhoid immunization, general health matters and water supply sanitation.

The following statistical tabulation is made from data furnished by county health officer, Dr. John D. Trawick:

Number of refugees housed in county	24,020
Number of refugee centers in county	46
Number of refugees ill and cared for in county	2,846
Number of immunizations given by the health department (does not include those by private physicians)	135,527
Number of county schools used for refugee centers	26

Emergency Division of Sanitary Engineering, Jefferson County Board of Health

My own activities were concerned with the organization of an Emergency Division of Sanitary Engineering of the Jefferson County Board of Health.

Following the receipt of a telegram from Mr. F. C. Dugan, chief engineer of the State Board of Health of Kentucky, I reported in Louisville and was immediately authorized to take over the sanitary engineering activities of the Jefferson County Board of Health in that portion of the county beyond the limits of the city of Louisville. On that same day Dr. Trawick, county health officer, appointed me chief sanitary engineer of Jefferson County, and with him I made a preliminary survey of some of the concentration and health centers. The following day the organization of an Emergency Sanitary Engineering Division for the county was begun. On February 6, having completed the emergency service for which I volunteered, and having the sanitation activities of the County Board of Health reasonably well organized, I left Louisville and returned to Boston.

A description of the organization of the Emergency Division of Sanitary Engineering and of the activities of this Division follows:

Organization

Under normal conditions the County Board of Health has but one sanitary inspector, Mr. J. R. Calhoun, whose duties relate largely to inspection of dairies and to general sanitation. The magnitude of the problem of sanitation in the county resulting from the evacuation of the city of Louisville, and the concentration of large numbers of refugees in temporary quarters, the failure of water supplies, and the sanitation of areas from which the flood waters eventually receded was so great that it became physically impossible for Mr. Calhoun alone to cope with the situation. He did, however, carry on a rigorous campaign of sanitation in a limited portion of the county in the vicinity of St. Matthews along the Shelbyville Road and northerly therefrom. It became my task, therefore, to organize a sufficient personnel to cover that portion of the county not being covered by Mr. Calhoun. It also became imperative, in view of the difficulties inherent in getting to and from the central part of Louisville, to establish headquarters in the county outside the city.

Personnel was recruited through the W. P. A. and the State Department of Health. To some extent volunteer workers reported for duty directly. Organization of personnel began on Friday, January 29, and men were put into the field for inspection work immediately. The total number of men associated with me during our activities reached a maximum of twenty-four, and three young women worked as stenographers for part of the time. Through a fortunate chance one of the first to be enlisted was Dr. E. E. Litkenhous, of the chemical engineering department of the University of Louisville, and whose efforts were successful in recruiting a number of other trained chemical engineers.

The members of this hastily recruited staff were largely engineers, although a few only had had previous training in sanitary engineering matters.

It should be noted as a matter of record that this group of men and women, obtained from many different sources and in the majority of instances without previous sanitary training, worked with enthusiasm, loyalty and intelligence. Time did not permit the carrying out of the work with the greatest degree of efficiency or with the least lost motion, nor was it possible to select, in every instance, the best qualified man to execute a task, but in view of the emergency the objective of the organization was to get the necessary work done and done as quickly as possible. Responsibility and authority were delegated to men as fast as problems arose requiring solution.

Headquarters for the emergency group were established at the Hikes School in Buechel, in which school had been established an emergency refugee hospital and refugee concentration center. The work of the engineers was hampered materially by the fact that there was only one telephone available in the school for communication with the city and other centers of activity, and also to some extent by the inadequacy of transportation facilities. Most of the engineers drove their own cars. Gasoline, for operating these, however, was purchased by means of credit cards supplied by the mayor's committee on relief.

Sanitation of Health and Refugee Centers

In general, the exodus of refugees from Louisville took place along the radial highways extending to the southeast of the city. This resulted in the housing of large numbers of people in temporary quarters such as schools, churches, warehouses and other buildings which could be utilized for this purpose. Furthermore, many of the refugees went into private homes. It was obvious at once that the sanitation of the refugee centers required immediate oversight as regards the disposal of excreta and the protection of the drinking water. The location of some of the refugee and health centers is shown in Fig. 2.

As previously pointed out, work of this character, for part of the county, was being carried out by Mr. Calhoun working from St. Matthews. The rest of the county, however, was being inadequately attended to, and to correct this situation several engineers were sent out beginning Friday, January 29, to investigate refugee centers and to report upon conditions found thereat. This work continued for several days. Not only were conditions investigated and reported upon, but word of mouth advice and recommendations were given to those in responsible charge. In some cases new privies were built, to replace inadequate or insanitary structures, chlorine compounds were left with instructions for use in the matter of disinfection of water, and general advice given relative to cleanliness.

The engineers not only engaged in activities relative to sanitation, but also reported to the medical unit the names of those found without immunization against typhoid fever, and assisted in the distribution of medical and relief supplies. While it was recognized that sanitation was the primary duty of our Division, it was also recognized that we should serve in every possible way to relieve distress and to advise the proper personnel engaged in other emergency activities as to needs uncovered by our inspections.

General County Sanitation

In addition to the concentration work at the health and refugee centers, a partial house to house canvass was made in the county, particularly in the area between Taylorsville Road and Bardstown Road, Prestonia, and Camp Taylor. The object of this work was to give advice relative to the precautions to be taken with respect to water supply and excreta disposal and in the matter of immunization against typhoid. The work also involved a certain amount of activity related to the refugee problem. Large numbers of individual houses were visited, but time did not permit visits to every house within the county. One of the reasons for this type of activity was to hold the organization together in order that men might be available for special duties as needs therefor arose.

Water Supply Sanitation

There were four special water supply problems referred to the Division for investigation and action. Two of these problems were within the county and two without.

At Camp Taylor, a suburban development south of and adjacent to the city limits, the normal water supply is obtained from the distribution system of the city of Louisville. As a result of inadequate pressure, Camp Taylor was without water for a considerable period of time. In order to provide for the eight or nine hundred dwellings within the area, the Camp Taylor Realty Company distributed water by means of tank trucks to these properties. The water was obtained from an abandoned quarry by pumping with a temporary pumping equipment into the tanks on the trucks. This quarry, while somewhat isolated and not subject to intensive pollution, was open to accidental or willful contamination, and a single dwelling house was located adjacent to the banks of the quarry but at a point where the land sloped away from the impounded water. A bacterial examination of the water showed moderate contamination only, but, in view of the obvious sanitary hazards, it was evident that proper chlorination was essential. Engineers from our Division visited the quarry on two or three different occasions, gave advice relative to the chlorination of the water in the tank trucks, and tested the chlorinated water with ortho-tolidine, in order to be assured that an adequate amount of chlorine was being applied.

At the Waverly Tuberculosis Hospital, located on high ground in the southwestern portion of the county, a temporary water supply was obtained by pumping from a small basin formed by a temporary dam across a surface stream coming through the grounds of the hospital. In addition to this surface supply, water from a well was being transported by truck to the hospital for drinking purposes after boiling. The normal water supply of the hospital is from the city of Louisville. Ordinarily pressure from the city mains is adequate to discharge water into storage tanks in the lower portion of the grounds whence it is pumped to the distribution system and elevated storage tank. Due to the low pressure of water in the city mains, water from this system was not available, and power failure prevented the use of the electrically operated pumps usually in service. It was necessary for the hospital authorities to install a small pump driven by a farm tractor to pump the temporary surface supply to the storage tanks ordinarily receiving city water, and then pump from these tanks by means of a steam fire underwriter pump to the above-mentioned elevated storage tank and distribution system.

At the beginning of the emergency at this hospital, no measures were taken to chlorinate the surface supply, but as soon as the condition was investigated by our Division, measures were immediately taken to install a temporary hypochlorite plant for the disinfection of the supply. This disinfection was carried on under the continuous supervision of one of the engineers of our Division, and the quantity of chlorine applied was sufficient to bring about disinfection of the entire distribution system. In about a week city water became available at pressure adequate to fill the receiving tank, and the emergency surface supply was abandoned. Chlorination, however, was continued to assure thorough disinfection of the distribution system and to correct any temporary contamination in the city water.

A request was received from Mr. Dugan to investigate the condition of the water works of Shepardsville, located just south of Jefferson County in Bullitt County. This town was visited at a time when it was necessary to use a boat to reach it. The investigation disclosed that the pumping station had been submerged and that the motors of the pumps would require removal and drying before they could be again used. The rehabilitation of this waterworks station had not been brought about at the time of the writer's withdrawal from Louisville, but conditions were known to Mr. Dugan, and the authorities in Shepardsville were aware of the measures necessary to put the waterworks back into service.

At Mr. Dugan's request, Lebanon Junction, a railroad center some distance from Louisville, also located in Bullitt County, was visited. In this instance the nearest point to Lebanon Junction which could be reached by automobile was five miles distant. Our representative reached Lebanon Junction with some difficulty due to the nearly complete isolation of the municipality by the flood waters. He found that the waterworks station and filter plant were almost completely submerged and that the inhabitants were depending on local wells for water supply. No previous instructions had been given the inhabitants of this municipality with respect to the boiling or disinfection of the water, nor as regards to sanitary precautions. Our representative conferred with the mayor and advised him relative to general sanitation and the need for boiling all water used for drinking and culinary purposes. Later, it is understood, two nurses and two doctors were dispatched to this community for immunization work and general health activities.

Disposal of Dead Animals

Prior to the recession of the flood waters from the inundated farm lands in the western part of the county between the Dixie Highway and the Ohio River, many estimates were made as to the number of live stock which had perished and whose carcasses would require disposal. These estimates, although based upon little accurate information, indicated that the problem of the disposal of the dead animals was one of considerable magnitude. On January 30, at a conference at St. Matthews, a method of handling the situation was determined upon. It was decided at this conference that the only practicable method to use for the disposal of the dead animals was to bury them as promptly as possible, and as near the places at which they were found as would be satisfactory from the sanitary viewpoint. This method involved the co-operation of Mr. Wood, county engineer, and Mr. Campbell, W. P. A. supervisor, as well as the personnel of the County Board of Health.

On Monday, February 1, the waters had receded sufficiently to permit the beginning of the work of disposing of the dead animals. Through the co-operation of Mr. Wood and Mr. Campbell, trucks and men were obtained, working from the county yard at Pleasure Ridge Park. Engineers of our Division were assigned the task of co-ordinating this work and passing upon the suitability of places of burying. This work was carried on as fast as it was possible to reach the animals, and in the first week of activity nearly one thousand animals were located and properly disposed of.

The work of disposal was facilitated by the action of a rendering company located in Salem, Indiana, sending to the flooded area a number of trucks into which were loaded some of the dead animals which were then transported to the rendering plant. A complete record of the number of animals found, the location of their burying places, and the number taken away by the rendering company was kept.

Disposal of Spoiled and Contaminated Food

Due to the flooding of warehouses, grocery stores and other places in which foodstuff for human consumption was stored, an enormous amount of such foodstuff was contaminated by the flood waters and rendered unfit for use. Inspection of foodstuffs was carried out by inspectors from the Federal Bureau of Food and Drugs, in collaboration with Mrs. Dugan of the State Board of Health. Practically all of the contaminated foodstuff was located within the city of Louisville, but the problem of finding a suitable place and method for the disposal of foodstuff was referred to our Division.

After some investigation and negotiation, the use of an abandoned quarry about two miles south of Buechel and about ten miles southeast of the court house in Louisville was secured for use as a spoiled food dump. It was estimated that the quarry would hold several thousand tons of material, and that it had more than ample capacity for the purpose. One of the engineers of our Division was assigned the task of supervising the initial use of this quarry for dumping foodstuff, and another member of the staff, who had under his control a truck and a small gang of W. P. A. laborers, was assigned the job of providing suitable roadways and the construction of a shelter for guards and inspectors. The first spoiled food reached the dump on Thursday, February 4, and continued for a while, at least, at the rate of about 75 tons per day. In order that the contaminated food might not be salvaged by unscrupulous persons, and in order that scavengers might not extract from the dump foods which might be used for human consumption, it was necessary to provide for guarding the dump at all times of the day. During the daylight hours inspectors and others were on duty, but at night it was necessary to place a military guard on watch. A method was also worked out whereby assurance could be obtained that truckloads of foodstuff leaving the city would be accounted for at the dump. By February 24, at the conclusion of dumping, the total quantity of foodstuffs disposed of at this point was 708 tons. About half of the material was burned and the remainder covered with earth.

Inspection of Flooded Homes

In the area west of the Dixie Highway many homes had been flooded to a depth of several feet. The condition of these homes after the flood waters had gone down was most deplorable, and in a great many instances the immediate reoccupancy of these homes would have been fraught with serious hazard to health. Furthermore, wells and cisterns had been flooded by contaminated river waters, and sanitary conveniences had been materially affected.

Although it was impossible wholly to prevent the reoccupancy of these houses, every effort was made to discourage people returning to them prematurely. House to house inspection was made and the owners contacted in many instances and given advice and warnings relative to the health hazards involved. In many instances, Dr. Ward Shacklett, quarantine officer for the district, passed upon the question as to whether people should or should not return to their homes. The work of this character was of necessity hastily organized and the policies adopted were based to a considerable extent upon expediency rather than upon scientific principles.

A summary of sanitation activities as of March 15, 1937, prepared by Mr. Maurice L. Miller, who carried on as acting sanitary engineer for the county after my return to Boston, shows clearly the magnitude of the sanitation problems that had to be met. Significant data from this summary are tabulated as follows:

Animal burials and disposal:	
(*a*) Large animals (approximate)	4,500
(*b*) Small animals and fowls (approximate)	12,185
Total	16,685

Water supplies (wells, etc.):	
(*a*) Total inspections	4,908
(*b*) Total samples taken	873
(*c*) Total analyses made	870
(*d*) Total chlorinations	523
(*c*) Total reports to owners as bad (estimated)	222
1. Schools	9
2. Residences (estimated)	213
Building surveys:	
(*a*) Total inspections (housing)	6,609
(*b*) Total inspections (sanitation) as of March 7, 1937	4,320
(*c*) Total inspections (schools), March 11, 1937	231
(*d*) Total number houses approved for occupancy	1,692
(*e*) Total buildings disinfected, March 17, 1937	108
Houses damaged beyond repair (estimated)	190
Houses requiring major repairs (estimated)	1,100
Houses requiring minor repairs (estimated)	1,728
Houses flooded to and over first floor (estimated)	2,988
Houses flooded basements only (estimated)	20
Privy survey:	
Total number inspected	602
(*a*) Inside toilets	26
(*b*) Recommended for construction	589
(*c*) Not recommended for construction	39

At the time the above data were compiled activity along the line of sanitation was still in progress and final figures are not available as yet.

Acknowledgment

At this point it seems fitting to gratefully acknowledge the assistance and co-operation of Dr. Alice N. Pickett, Chairman, County Board of Health, Dr. John D. Trawick, County Health Officer, Dr. Smock, Deputy County Health Officer, Mr. Calhoun, County Sanitary Inspector, Mr. J. K. Hoskins, United States Public Health Service, Mr. and Mrs. Dugan and Mr. Harris of the State Board of Health, Dr. Leavell, City Health Officer, Mr. Wood, County Engineer, Mr. Wheeler, County Tax Commissioner, Mr. Burnett, State Highway Commissioner, Mr. Campbell, W. P. A. Supervisor, Dr. Brock of the Waverly Sanatorium, Dr. Dwyer and Major Arnold of the Buechel Health Center, as well as the many workers at this Center, the trustees of the Hikes School, and, above all, the loyal staff of the Emergency Division of Sanitary Engineering of Jefferson County, each one of whom should receive special mention.

It is also appropriate to record the patience, fortitude and courage of the people of Louisville and Jefferson County, and the willingness of those not directly affected by the flood to help those less fortunate.

Emergency Organization for Disasters

Based upon personal experience at Louisville and published accounts of emergency activities at times of other disasters, it is my opinion that there should be established a skeleton organization prepared to undertake the oversight of emergency activities when occasion therefor shall arise. It is my opinion also that this skeleton organization should be made up of officials from permanent state and other governmental agencies. Volunteer and semi-public organizations, admirable as they may be in many respects, particularly as regards post-disaster rehabilitation and the raising of relief funds, are often too cumbersome to function with the speed which is called for in serious disasters.

Outline of Organization

There are five major divisions under which emergency activities at time of disaster are likely to be carried on, namely:

1. Medical.
2. Sanitation.
3. Service of supplies.
4. Police and quarantine.
5. Protection and salvage of property.

The relative importance of these several divisions will depend upon the type of disaster.

The several divisions should be headed by the state official who is best qualified by training and experience and ability to organize the type of work his division would be called upon to do in time of disaster. The Board should select one of its members or possibly some one outside of the Board to act as chairman or chief executive officer, whose duties would be to co-ordinate the work of the several agencies involved.

Tentatively, I would suggest that the State Commissioner of Health, or the head of the National Guard, serve as the chairman of such a board for emergency activities.

The chief medical officer, who might be the State Commissioner of Health, assisted by physicians, nurses and technicians, would take over the work involved in the immunization, hospitalization, emergency medical aid and food inspection.

The chief sanitary engineer, who might well be the State Sanitary Engineer, assisted by other engineers, chemists and bacteriologists, with laborers and foreman recruited from the W. P. A. or from the State Department of Public Works or its equivalent, would take over the protection of water supplies, emergency chlorination, disposal of excreta and general sanitation.

The division of the service of supplies might well be in charge of the State Engineer or his equivalent, who would have under him traffic managers, supply clerks and communication engineers. This division would take over the problems relating to evacuation and housing of refugees, the transportation of refugees and supplies, procurement and distribution of food, clothing, bedding and other supplies, and the establishment of emergency systems of communication. This division should co-ordinate the activities of volunteer and semi-public relief agencies.

The division of police and quarantine might well be in charge of the Commander of the State Police or the commanding officer of the National Guard who would co-ordinate the work of local and State Police and of the National Guard. Duties of this division would be the protection of lives and property, convoying of food and refugees and supplies, and enforcement of quarantine orders.

The division functioning to protect and salvage property could be in charge of the State Fire Marshal or his equivalent, whose duties would be to co-ordinate the activities of the fire departments, of salvage and protective associations, and of building inspectors. The duties of this division would be related to fire protection and salvage of property and to building and plumbing inspections.

It will, of course, be necessary for this emergency organization to secure the co-operation of private and semi-public organizations like the Red Cross, but the responsibility and authority for disaster control should rest wholly with the official organization.

In normal times a skeleton organization made up of the heads of the five divisions should meet from time to time in order to work out the general policies to be followed, and to arrange the details of mobilization of personnel and resources at times of disaster.

In time of emergency it is important that authority for the requisition of supplies and transportation be vested in the chiefs of the several divisions, and that a standing appropriation for disaster relief should be at the disposal of the emergency organization.

United States Public Health Service Reserve Corps

For most effective action in matters of sanitation, whenever a major calamity occurs, it is essential that close co-operation between the State Department of Health and the United States Public Health Service be provided. It would seem very desirable, therefore, that there be formed under the auspices of the Public Health Service a reserve corps of non-paid physicians, nurses and sanitary engineers who could be called out when the state personnel is inadequate in numbers to carry on. Such a reserve corps could be made up of employees of state health departments and of qualified persons not in any official position. This reserve corps should be sworn into the service during normal times and should have the authority to incur travel and subsistence expenses when ordered to active duty by the Surgeon General. This reserve corps might well be subject to regional mobilization once a year for instruction and inspection.

Conclusion

I well realize that the suggestions made are very general, and the whole matter of organization for disaster control is one deserving of much and careful consideration. The present-day city is such a complex and delicate organism, depending upon the uninterrupted continuation of so many services, that fires, floods or other natural disasters bring about a condition of extreme chaos with great hazard to life and property. Such disasters have occurred in many instances in this country since the beginning of the century, and will continue to occur. We must be prepared to meet them.

Of General Interest

BOSTON SOCIETY OF CIVIL ENGINEERS SCHOLARSHIP IN MEMORY OF DESMOND FITZGERALD AWARDED TO LESLIE W. LENFEST, STUDENT AT NORTHEASTERN UNIVERSITY

Leslie W. Lenfest of Watertown, Mass., a senior student in civil engineering in the School of Engineering at Northeastern University, was awarded the Desmond FitzGerald Scholarship of the Boston Society of Civil Engineers on May 5, 1937. The presentation of the Scholarship of $100 was made at a meeting of students of the School at Jordan Hall, by Karl R. Kennison, Vice-President of the Boston Society of Civil Engineers.

PROCEEDINGS OF THE SOCIETY

MINUTES OF MEETINGS

Boston Society of Civil Engineers

APRIL 21, 1937. — A regular meeting of the Boston Society of Civil Engineers was held this evening at the Engineers Club, and was called to order by the President, Arthur D. Weston. Seventy members and guests were present. Fifty-two attended the buffet supper.

The following were elected to membership at the Board of Government meeting on April 8, 1937:

Grade of Student: Arnold V. Davis, Chesley F. Garland, Joseph Higgins, Peter R. Vandersloot.

President Arthur D. Weston introduced the speaker of the evening, Prof. Charles F. Brooks, Professor of Meteorology at Harvard University and Director of the Blue Hill Meteorological Observatory of Harvard University, as well as of the Mount Washington Observatory, who gave a very interesting talk on "Weather Forecasting, with Comments on Recent Floods." The observations of atmospheric conditions, the data obtained at the Mount Washington Observatory and other stations, and their significance and interpretation were subjects considered. The effect of the White Mountain range on approaching storms and precipitation in the drainage basins of New England were also discussed, as well as the storm characteristics at many other sections of the country. The talk was illustrated with lantern slides.

The meeting adjourned at 9 P.M.

EVERETT N. HUTCHINS, *Secretary.*

MAY 19, 1937. — A regular meeting of the Boston Society of Civil Engineers was held this evening at the Engineers Club and was called to order by the President, Arthur D. Weston, at 7 P.M. Sixty-three members and guests were present. Fifty-four persons attended the buffet supper.

The President announced the deaths of the following members: George H. Brazer, elected a member April 17, 1907, and died April 20, 1937; and Leonard C. Wason, elected a member April 21, 1897, and died April 30, 1937.

The Secretary reported the election of new members, on May 19, 1937, as follows:

Grade of Member: Paul N. Anderson, William R. Benford, Albert G. Dietz, Miss Lillian F. Edwards, Viking Enebuske, Daniel C. Frost,* Howard E. Gale, Jr.,† Leslie J. Hooper, Harold W. Legro, Charles V. Maccario,* Walter F. Macdonald, Alden S. Marble, Hermon S. Swartz, Robert H. Verner.*

Grade of Junior: Franklin P. Parker, William A. Redfield,† David C. Wiggin, Jr., Robert C. Zacher.†

Grade of Student: Frank R. Damassa, Paul C. Danforth, Harry L. Hughes, Burritt F. Leighton, Frank W. Sarnow.

The President announced that there would be no regular meeting in June, but that an excursion is planned for June 23, to include visits to construction work on the new North Metropolitan Sewer, the Newburyport Turnpike, dinner at Hampton Beach, N. H., and visits to flood protection work along the Merrimack River.

The President then introduced the speaker, Mr. Clarence E. Boesch, Chief, Flood Control Division, War Department, United States Engineer's Office, Providence, R. I., who gave a very interesting talk on "The Recent Floods on the Mississippi River — the Flood Flows and Damages Incurred, — and the Effectiveness of the Flood Control Measures already Carried Out." The talk was illustrated with lantern slides.

The meeting adjourned at 9 P.M.

EVERETT N. HUTCHINS, *Secretary.*

Sanitary Section

APRIL 7, 1937. — A special meeting of the Sanitary Section of the Boston Society of Civil Engineers was held this evening. Preceding the meeting, twenty-one members gathered at Patten's Restaurant for dinner.

The meeting was called to order by the Chairman, Richard S. Holmgren, at 7.10 P.M., in the Society Rooms, with thirty-two members and guests present. Robert Spurr Weston, consulting engineer, presented a paper on "The Treatment of Wool-Scouring Wastes," in which he described the operation of such treatment plants in England and the United States. An interesting discussion followed in which Messrs. Coburn, Fair, Edwards and Bogren took part. The meeting adjourned at 8.40 P.M.

RALPH M. SOULE, *Clerk.*

Designers Section

APRIL 14, 1937. — The April meeting of the Designers Section was held at the Society Rooms on April 14, 1937, at 6.30 P.M.

The Secretary's report of the March meeting was read and approved.

It was then —

Voted, To approve the recommendation of the "Committee on Relations of Sections to the Main Society," that Article II, Membership, of the By-Laws of the Sections be amended so as to read as follows:

ARTICLE II. — *Membership*

SECTION 1. Members of the Boston Society of Civil Engineers in all grades shall be members of the Sections except that membership in the Northeastern University Section is limited to members of the Society in all grades, who are students, graduates, or members of the Faculty of Northeastern University.

SECTION 2. Only members of the Northeastern University Section who are students at Northeastern University are eligible to hold office in that Section.

* Transfer from Grade of Junior.

† Transfer from Grade of Student.

This approval was forwarded to the Secretary of the Main Society.

The Chairman then introduced the speaker of the evening, Mr. John C. Moses, Engineer for the State Department of Public Works, and a member of the Section. Mr. Moses spoke on "The Repair of Flood-Damaged Bridges." The talk was illustrated with pictures.

The meeting adjourned at 7.40 P.M.

The attendance was thirty-one.

J. D. MITSCH, *Clerk.*

MAY 12, 1937. — The May meeting of the Designers Section was held at the Society Rooms on May 12, 1937. The Secretary's Report of the April meeting was read and approved.

The Chairman then introduced the speaker of the evening, Mr. Miles N. Clair, Vice-President of The Thompson and Lichtner Company, Inc. Mr. Clair gave an interesting talk on "The Relation of the Testing Laboratory to the Engineer and Architect." The talk was illustrated by slides showing the instruments and methods used in the modern testing laboratory.

A question period followed the talk and the meeting adjourned at 9 P.M.

The attendance was forty-five.

J. D. MITSCH, *Clerk.*

Northeastern University Section

MAY 26, 1937. — A regular meeting of the Northeastern University Section of the Boston Society of Civil Engineers was held in Room 201 L on Wednesday, May 26, 1937. The meeting was called to order at 1.30 P.M. by Vice-Chairman Lester S. Perry, who announced that at the close of the meeting election of officers for the year 1937–1938 would be held.

A natural-color talking picture of highway construction in California was received with great enthusiasm, especially a portion of the film depicting the prevalence of natural physical curves.

At the conclusion of the picture, the following Division B members were unanimously elected to office:

Vice-Chairman — Peter R. Vandersloot.
Vice-Clerk — Lewis W. Pollard.
Executive Committee — Orland T. Pritchard, Daniel J. Putzel, Jr.

ROBERT C. SANDERSON, *Vice-Clerk.*

APPLICATIONS FOR MEMBERSHIP

[July 1, 1937]

THE By-Laws provide that the Board of Government shall consider applications for membership with reference to the eligibility of each candidate for admission and shall determine the proper grade of membership to which he is entitled.

The Board must depend largely upon the members of the Society for the information which will enable it to arrive at a just conclusion. Every member is therefore urged to communicate promptly any facts in relation to the personal character or professional reputation and experience of the candidates which will assist the Board in its consideration. Communications relating to applicants are considered by the Board as strictly confidential.

The fact that applicants give the names of certain members as reference does not necessarily mean that such members endorse the candidate.

The Board of Government will not consider applications until the expiration of fifteen (15) days from the date given.

For Transfer from Grade of Junior to Grade of Member

MACDONALD, GEORGE ALLO, River Edge, N. J. (b. June 15, 1908, Salem, Mass.) Was graduated from Northeastern University, 1930, with degree of bachelor of civil engineering. Experience: Co-operative periods, April, 1927, to September, 1927, with Charles R. Berry, civil engineer, assistant on field engineering, draftsman and chief of party on surveys; October, 1927, to June, 1930, with New York, New Haven & Hartford Railroad, alternating five-week periods, as rail inspector and chainman on Waterbury, Boston and Providence Divisions; July, 1930, to September, 1930, with Massachusetts Department of Public Works as Grade II civil engineer; October, 1930, to date, with Westinghouse Electric and Manufacturing Company as student engineer; engineer in transportation and central station departments on solution of problems pertaining to railroad electrification, high-speed, self-propelled trains, and central power and industrial power plants. Now sales engineer, New York office, Westinghouse Electric and Manufacturing Company. Refers to *H. B. Alvord, C. O. Baird, Jr., C. S. Ell, E. A. Gramstorff, G. H. Meserve.*

ADDITIONS

Members

PAUL N. ANDERSON, 19 Kosta Street, Worcester, Mass.
WILLIAM R. BENFORD, 17 Observatory Avenue, North Providence, R. I.
ALBERT G. DIETZ, Massachusetts Institute of Technology, Room 1–230, Cambridge, Mass.
LILLIAN F. EDWARDS, South Orleans, Mass.
VIKING ENEBUSKE, 397 Commonwealth Avenue, Boston, Mass.
DANIEL C. FROST, 66 Mountain Avenue, Bloomfield, N. J.
HOWARD E. GALE, Jr. 35 Moultrie Street, Dorchester, Mass.
LESLIE J. HOOPER, Holden Street, Holden, Mass.
CHARLES V. MACCARIO, 970 Salem Street Malden, Mass.
WALTER F. MACDONALD, 173 Davis Street, Wollaston, Mass.
ALDEN S. MARBLE, Pearl Hill Road, Fitchburg, Mass.
A. ALBERT MINICHIELLO, 18 Ashley Street, East Boston, Mass.
HERMON S. SWARTZ, 97 Dalby Street, Newton, Mass.

Juniors

WILLIAM A. GRADY, 17 Sheridan Circle, Winchester, Mass.
FRANKLIN P. PARKER, 119 College Avenue, Danville, Va.
WILFRED C. PITTS, 66 Warrington Street, Boston, Mass.
WILLIAM A. REDFIELD, R. D. No. 1, Middletown, N. Y.

Students

FRANK R. DAMASSA, 76 Westland Avenue, Suite 7, Boston, Mass.
PAUL C. DANFORTH, 9 Gould Street, Danvers, Mass.
HARRY L. HUGHES, 64 Sumner Road, Brookline, Mass.
BURRITT F. LEIGHTON, 506 Ash Street, Brockton, Mass.

DEATHS

JOSEPH DRISCOLL . .	May 26, 1937
HARRISON P. EDDY . .	June 15, 1937
CHARLES H. EGLEE . .	July 4, 1937
LEONARD C. WASON . .	April 30, 1937

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BOSTON SOCIETY OF CIVIL ENGINEERS

FOUNDED 1848

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James F. Brittain
Samuel M. Ellsworth
LeRoy M. Hersum
(Term expires March, 1938)

Henry B. Alvord
George C. Houser
Albert E. Kleinert
(Term expires March, 1939)

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Thomas R. Camp
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H. B. Kinnison
Karl R. Kennison
William F. Uhl

Publication

Everett N. Hutchins, *Chairman*

J. Stuart Crandall
Gordon M. Fair
Waldo F. Pike

Membership and Publicity

H. P. Eddy, Jr., *Chairman*

W. F. Donovan
H. G. Dresser
A. B. Edwards
G. A. Graves
L. M. Hersum
K. C. Reynolds
F. N. Weaver

Library

Eugene Mirabelli, *Chairman*

Henry B. Alvord
Edward S. Averell
Kimball R. Garland
C. F. Joy, Jr.
E. A. Varney

Social Activities

John H. Harding, *Chairman*

Edward F. Kelley
Joseph D. Guertin

Relations of Sections to Main Society

Herman G. Dresser, *Chairman*

Richard S. Holmgren
Alexander J. Bone
G. L. Cheney

Membership Records

John B. Babcock, 3d, *Chairman*

J. Stuart Crandall
A. B. Edwards
Everett N. Hutchins

Run-Off

Arthur T. Safford, *Chairman*

H. K. Barrows
H. P. Burden
R. W. Horne
S. S. Kent
F. H. Kingsbury
H. B. Kinnison
R. R. Marsden
William Noyes
L. B. Puffer
H. M. Turner
W. F. Uhl
F. E. Winsor

Welfare

Ralph W. Horne, *Chairman*

John R. Freeman Fund

Charles T. Main, *Chairman*

Charles M. Allen
Robert Spurr Weston
Howard M. Turner

Desmond FitzGerald Award

Albert Haertlein, *Chairman*

Frank E. Winsor
Charles J. O'Donnell

1936 Flood Committee

Howard M. Turner, *Chairman*

(See April, 1936, Journal for Complete Membership)