STABILITY OF NATURAL EARTH SLOPES AND CONSTRUCTED EMBANKMENTS*

(A GUIDE FOR FARMERS AND SCIENTISTS)

by A. D. WALSH SPARKS

Introduction

Modern farmers are being forced to increase the productivity of their farms in order to satisfy expanding economic and consumer requirements.

Additional capital works such as new roads, canals and dams, or the cultivation of steeper slopes of farming land may become necessary.

The stability of earth slopes, embankments and hillsides is therefore a factor which is important to the farmer, both for economic reasons and because the safety of human lives may be affected by badly designed dams and embankments.

The object of this paper is to provide the farmer and the scientist with a summary of some of the factors which should be considered.

This paper will be sub-divided into three categories, namely:

(*a*) the stability of earth dams;
(*b*) the stability of road embankments; and
(*c*) the stability of natural hillsides.

The Design and Stability of Earth Dams

In the case of farm dams built to a height of less than 10 feet it is usually sufficient to provide an adequate spillway and earth side slopes of approximately 1 vertical to 3 horizontal units. However, special precautions should be taken for larger dams, and may also prevent financial losses in the smaller dams. Because the stability of a dam is also affected by the over-topping of the dam and matters other than Soil Mechanics theory, the author will also mention these other problems.

Location of the Dam

The location of the dam is chosen on the basis of the following factors:

(i) the narrowness of the valley;
(ii) the size of the watershed;
(iii) the proximity of the irrigated lands and canals;
(iv) the available volume of storage in the proposed dam;
(v) the possibility of additional canals for leading the water into the dam.

These five factors may be assessed from contour maps of the area (see Ref. 1, Ref. 2).

(vi) In addition, the geology of the dam site must be considered. In dolomite or limestone areas, underground seepage channels and sinkholes can cause large water losses from the dam. Fissured shales and sand lenses also cause water to be lost and may cause springs or otherwise adversely affect the stability of the downstream slope of the dam.

Fissures in rocks can often be sealed by pumping concrete grout down drill holes into the rock.

In certain areas of South Africa "collapsing sands" soften and settle upon being wetted if a load exists on the sand. Stiff fissured clays can also soften with time.

If water is poured into a saucer on which stands a mound of sugar, it will be noticed that the sugar slumps and slides downwards on the soft layer of syrup which is formed under the mound. In a similar manner an earth dam built on a soft horizontal layer of clay may slump and slide outwards in both the upstream and downstream directions. It may be necessary to remove a soft foundation clay, even though clay is the best soil for preventing seepage losses.

Water Run-off

When assessing the quantity of water which will run into the dam, two separate calculations should be made:

(i) The first calculation should be a conservative estimate of the available volume of water which is available for storage. The object of this calculation is to determine whether the dam is an economical proposition. For large dams the "hydraulic mass diagram" is used (Ref. 3, 4). In this diagram the Accumulated Flow (gallons) in the stream is plotted against time. To plot this diagram it is necessary to gauge the stream flow for a number of years by using measuring weirs.

Alternatively, a rough calculation may be made by using the average monthly rainfalls if a correction is made for evaporation and the absorption of water into the soil.

(ii) The second calculation is to determine the required spillway capacity. It is obvious that this must depend upon the worst flood conditions.

Unfortunately many hydraulics textbooks quote overseas rainstorm figures which are inadequate for South African design purposes.

In May 1905 a rainfall of 17.65 inches was recorded during 24 hours in Durban, and 15.65 inches fell at Mariannhill in 15 hours. These values exceed most overseas figures.

Spillway Flood Calculations

The peak rate of flow into a dam will depend on the direction of travel of the rainstorm as well as on its duration and intensity. The earlier weather conditions, and the shape and nature of the catchment area will also affect this flow.

In order to estimate the peak flow, it is necessary to estimate the "time of concentration" for the area.

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* This paper was received too late to be read and discussed at the Congress.

The "time of concentration" is defined as the average time required for the rain falling on the boundary of the catchment to reach the dam. This time is usually about 10 to 45 minutes for a farm dam.

Nomogram Charts are available for more accurate assessment of the time of concentration (Ref. 1, p. 49; Ref. 3, p. 5-00). A formula by Izzard is also given in Ref. 4, p. 48.

Rainfall statistics show that short duration storms have greater intensities (inches per hour) than long duration storms.

For most catchment areas the maximum discharge of stormwater occurs when the duration of the storm equals the time of concentration of the area.

For estimating the peak flood under South African conditions the author suggests that one should assume that the average storm intensity (inches per hour) is —

$$i = \frac{19.0}{1.9+t} \text{ inches per hour} \quad \ldots \quad \ldots \quad \ldots \quad (1)$$

where t = storm duration = time of concentration (hours)

$$\text{or} \quad i = \frac{1140}{114+t} \text{ inches per hour} \quad \ldots \quad \ldots \quad \ldots \quad (2)$$

where t = storm duration = time of concentration (minutes)

(According to these formulae a storm lasting 1 hour will fall at an average intensity of 6.5 inches per hour.)

Having determined the storm intensity i from equations (1) or (2), the run-off of stormwater from the catchment area may then be calculated from the formula—

$$\begin{aligned} Q &= 1.008 \text{ k.i.A cubic feet per sec.} \\ &= \text{k.i.A cubic feet per sec. (approx.)} \ldots \quad (3) \end{aligned}$$

where

A = watershed area in acres.

k = a run-off coefficient which is equal to the proportion of rainwater which reaches the dam.

(Typical values for k are:

Wooded areas	0.01 to 0.20
Parks and open spaces, meadows and cultivated areas	0.05 to 0.30

The author suggests that a value of 0.4 be used, as the value of k must depend on earlier weather conditions.)

The minimum spillway proportions must be determined after the calculation of the run-off Q in equation (3). Spillway formulae are dealt with in Appendix 1.

The Stability of the Dam

Two main factors influence the stability of the dam. These are firstly the types of soil chosen and secondly the relative geometrical positions of the different soil types in the dam.

Coarse sandy materials usually possess good strength characteristics, but allow the water to percolate freely through the dam. Clayey soils are almost impermeable, but they give unreliable strengths unless compacted under engineering supervision.

For this reason clayey soils are usually used for an impermeable centre core wall which extends downwards into the dam sub-base. The sandy soils are used for the upstream and downstream banks on both sides of this core wall (see Fig. 1).

Difficulty is experienced in convincing farmers that an earth dam requires flatter upstream and downstream slopes than the angle of repose of the freshly deposited soil.

It can be proved by theory and practice that a steep dry slope which is stable may become unstable when water seeps out of the slope. This instability is caused mainly by the water pressures in the soil and also by the fact that the moisture increases the weight of the soil. The *downstream* slope of a dam must therefore be flatter than the angle of repose of the soil.

Whenever the water level in the dam is lowered, water will also flow backwards into the dam from the voids in the dam embankment. (This is known as the 'Draw-down condition'.) For this reason the *upstream* slope of the dam must also be flatter than the angle of repose of the soil.

Water must be diverted before it seeps out of the downstream slope in the form of springs (e.g. see Fig. 3). Graded stone filters below the toe of the downstream slope will effectively gather the permeating water before it appears on the downstream slope (see Figs. 1, 2, 4). These filters will also lower the water table and water pressures in the embankment. On no account should an impermeable blanket be laid on the *downstream* slope to "prevent" water seepage, because water pressures will build up behind the blanket.

Graded stone filters should be provided in all large dams, and they will also increase the stability of smaller dams. The grading of these stone sizes should be done after a sieve analysis has been made on the available materials. A grading theory has been developed in order that the pores of a coarse aggregate may not be blocked by smaller particles from the adjacent finer soil. (See Ref. 1, p. 118.) If the filters are blocked, portions of the dam may become unstable.

A few permanent vertical standpipes ($1\frac{1}{2}$ ins. diameter) will allow periodic checks on the level of the water table in the embankment (see Fig. 3). If the filters become ineffective the water table will rise.

An alternative dam construction is shown in Fig. 2a. This is suitable for an area where there is a shortage of sandy material.

A cut-off wall may be built at a site where there is little clay (Fig. 5). Alternatively, polythene sheets, or a clay blanket, may be used (Fig. 4). However, the clay blanket shown in Fig. 4 may be unstable in dams in which the draw-down condition occurs (e.g. dams used for irrigation purposes).

Other practical details

Every attempt must be made to reduce the seepage water pressures before the water reaches the downstream slope. For example, the cut-off wall in Fig. 5 reduces seepage pressures in the sand layer below the downstream clay layer. The provision of gravel-filled relief walls provides further water pressure relief (Fig. 5).

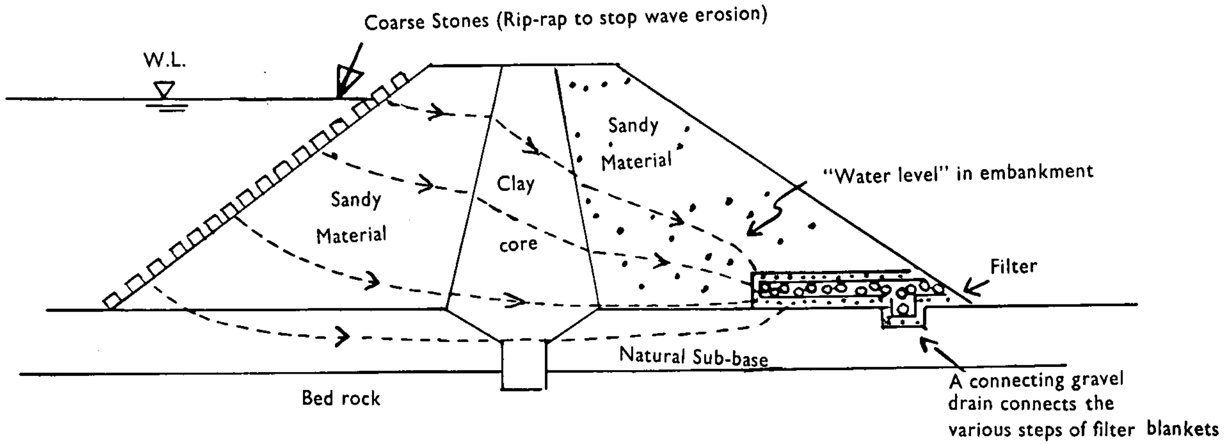


Fig. 1

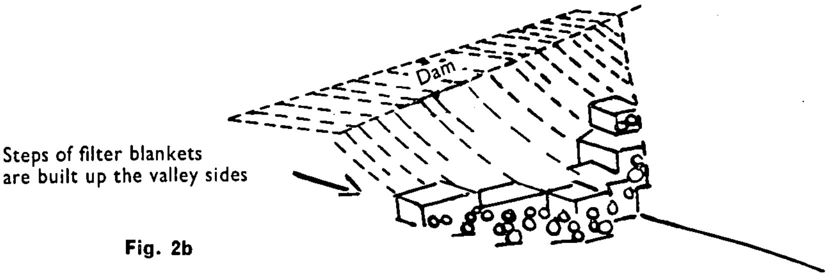


Fig. 2b

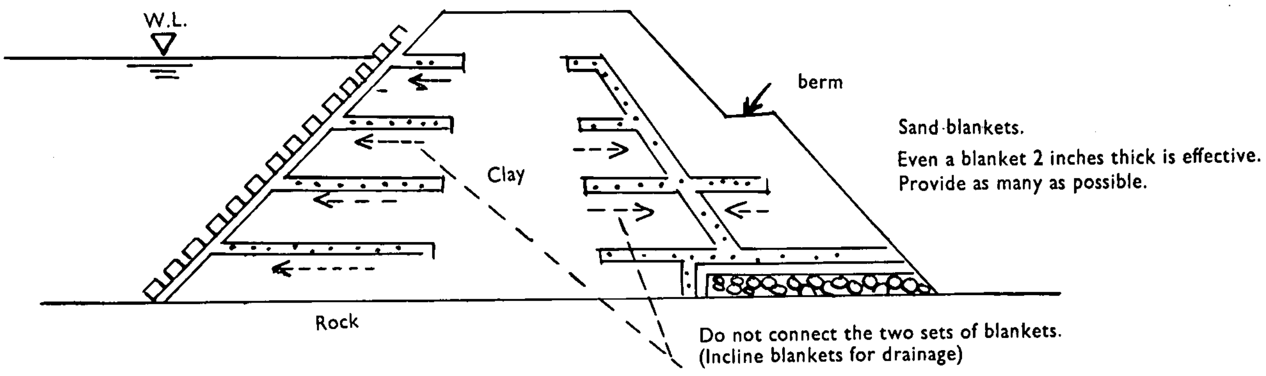


Fig. 2a

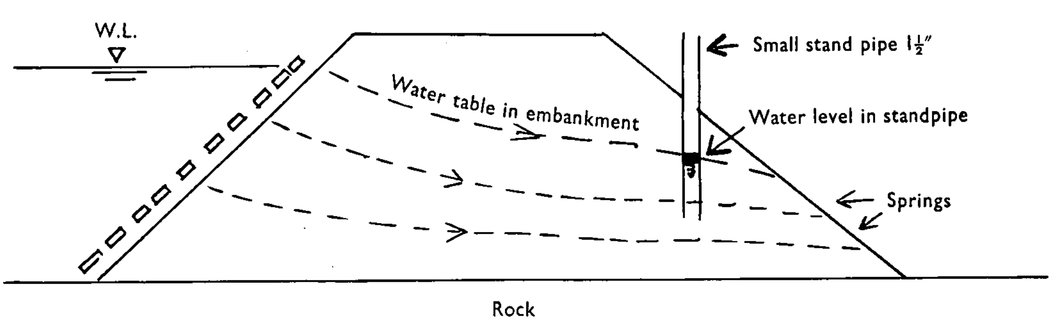


Fig. 3

Dam without filter

The upper surface of an earth embankment will always settle. The upper surface of the eventual earth embankment should have a free-board of *at least* 2 ft. 6 ins. or 3 ft. above the spillway level. In addition, an extra height allowance for settlement should be provided. This settlement allowance may be approximately one-tenth of the height of the embankment.

The pipes which lead water through the dam embankment should not be provided with a main valve below the dam (Fig. 6a). For example, if concrete or asbestos-cement pipes are used, settlement of the embankment will cause the pipe joints to open. The escaping water will cause springs and instability on the downstream slope.

Only in the case of steel pipes, and perhaps certain plastic pipes, may the valve be placed on the downstream side of the dam.

Special care should be taken to ensure that every pipe through the embankment rests on firmly tamped soil which will not settle away from the bottom of the pipe to leave a possible erosion channel under the pipe.

Seepage baffles in the form of concrete blocks should be cast against the soil at periodic intervals around the pipe (see Fig. 7).

The valve spindles in a dam may either be inclined (as in Fig. 6b) or attached to a tower as in Fig. 7. The inclined spindle should be provided with universal couplings to allow for settlement of the embankment. Periodic cleaning and scouring of the dam will prevent debris from clogging these valves.

In certain dams it may be advisable to provide an additional emergency safety spillway. This consists of a concrete spillway (Fig. 8) which is covered with earth in such a manner that overtopping of the earth embankment will occur at this portion first. The concrete spillway prevents the erosion of the whole embankment. Only if a civil engineer is consulted should one consider the use of a thick polythene sheet instead of a concrete apron. Care must be taken that the water does not enter below the sheet or suck it up due to a vacuum in the water as it goes over the spillway.

A dry soil is compacted with difficulty because the grains do not easily slide over each other. A saturated soil is also difficult to compact as the pore water requires time to flow out of the soil. Soil is therefore most easily compacted at an intermediate water content known as the "optimum water content".

The optimum water content for sands is approximately 10 per cent, and may be as high as 40 per cent for clays.

Dam embankments should usually be compacted at a water content just less than the optimum water content As a rough guide, do not compact the soil when it is "spongy"; and do not compact clayey soils in wet weather or immediately after heavy rains. This has a large influence on the strength of the embankment.

Soil tests

The following tests should be performed before a large dam is designed:

(*a*) Atterberg Limit tests, and linear shrinkage tests. This is to classify the soils.

(*b*) Permeability tests to determine the ease with which water can permeate through the soils.

(*c*) Optimum water content tests to assist with the compaction control of large dams.

(*d*) Sieve analysis of the filter material to determine the particle size grading curve. Sieve analysis (and hydrometer grading tests) can also be used to estimate the permeability of the soil.

(*e*) In large dams sheer strength tests should be performed both before and during construction especially when dealing with clayey material. These tests indicate the strength of the material and the permissible slopes for the banks.

(*f*) Inspection test pits should be made in the proposed sub-base for the embankment.

Shear strength tests

A shear box consists of a metal box which is divided horizontally into an upper and a lower portion (see Fig. 8a). A bearing plate in the top portion transmits the force N to the soil. A horizontal force F is applied to the upper portion to cause the soil to shear at the level X - X.

Obviously in the case of a sand an increase in the value of force N will require an increase in the failure value of force F. The failure combinations of F and N are plotted in Fig. 8b. The slope of this line is known as the angle of friction ϕ of the soil. In the case of a sand only a slight value of F is required to cause failure if there is no force N. However, in the case of clays the cohesion between the soil grains is such that even when the force N is zero an appreciable value of F is required for failure. If this particular value of F is divided by the cross-sectional area A of the shear box, the resulting value F/A is known as the "cohesion c" of the clay (see Fig. 8b).

The shear box is not used to find the cohesion c and the angle of friction ϕ of clays. Instead, the usual test for a clay is the "saturated undrained triaxial test" performed on soaked samples which are compacted at approximately "optimum water content".

The values of c and ϕ for the soil are used to calculate a suitable slope for the dam. This suitable slope is also dependent on the weight of the soil γ (lb/ft^3), and the working height H_W of the slope.

The chart in Fig. 10 was derived by the author with aid of an electronic digital computer. In this chart H_W is measured in feet. The weight γ of the soil is usually 125 (lb/ft^3). The cohesion c is expressed as pounds per square foot. This chart has been calculated for a slope of 1 vertical unit in 3 horizontal units. Charts for other slopes have also been obtained.

The chart should be entered with the known values of H_W, c, ϕ and γ in order to find the factor of safety F. If F is found to be 1.0, or less, the bank will fail. The value of F should be greater than 2.5, unless the dam is supervised by engineers, in which case a lower value of F can be used. The value of F will be increased if flatter slopes are used.

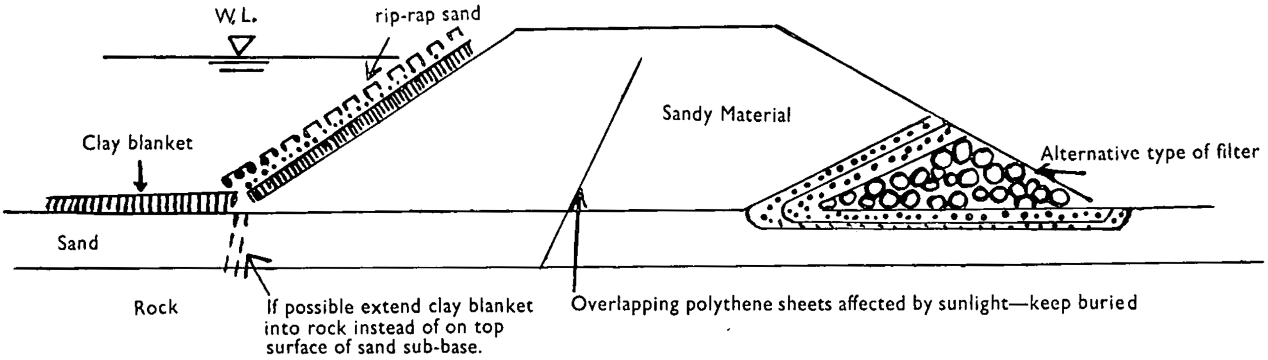


Fig. 4 Note: All above slopes have been drawn steeper than the slope of an actual dam

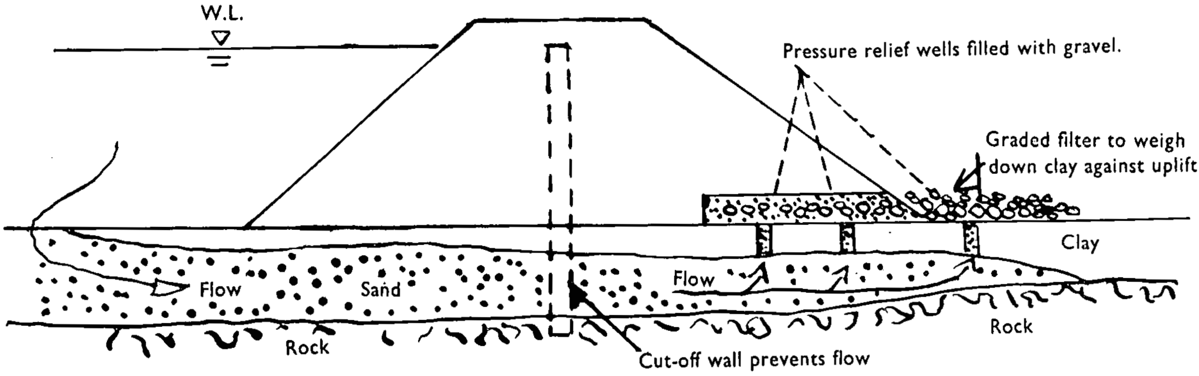
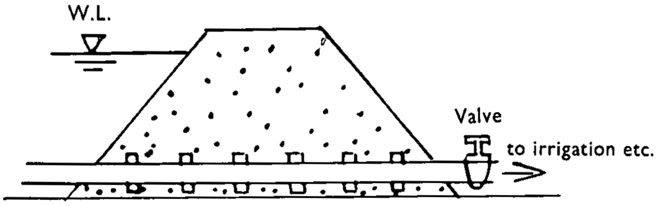


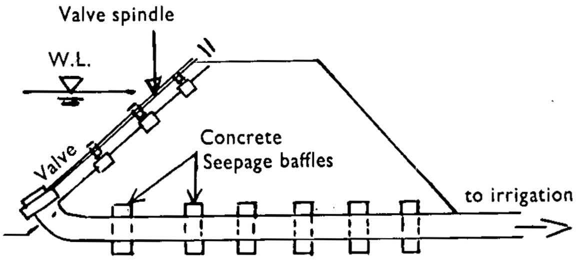
Fig. 5



Incorrect Method

(Only steel pipes with strong joints may have valve below dam)

Fig. 6a



2 types of valve: Either a tower in centre of dam, or an inclined spindle as shown.

Correct Method

Fig. 6b

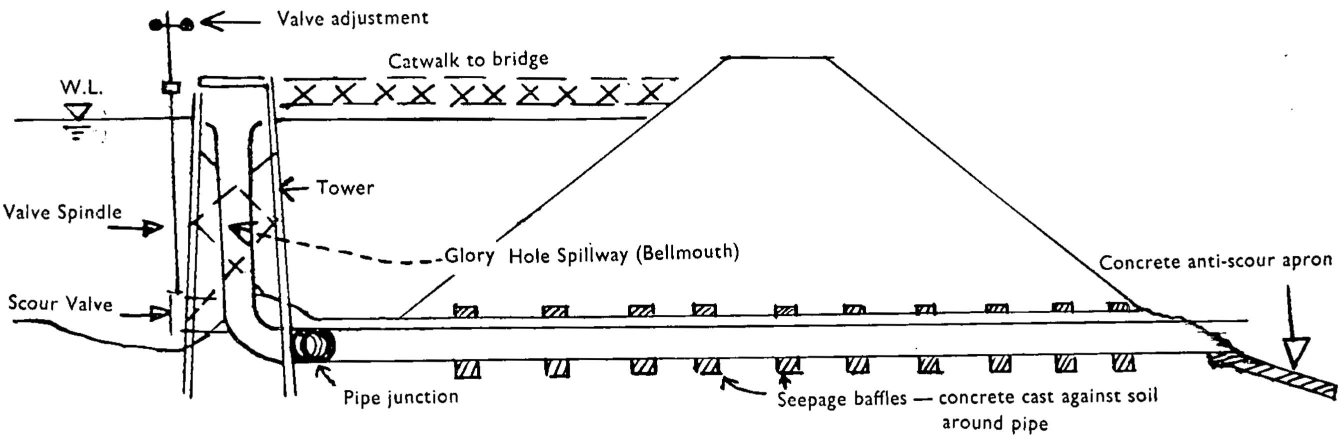


Fig. 7

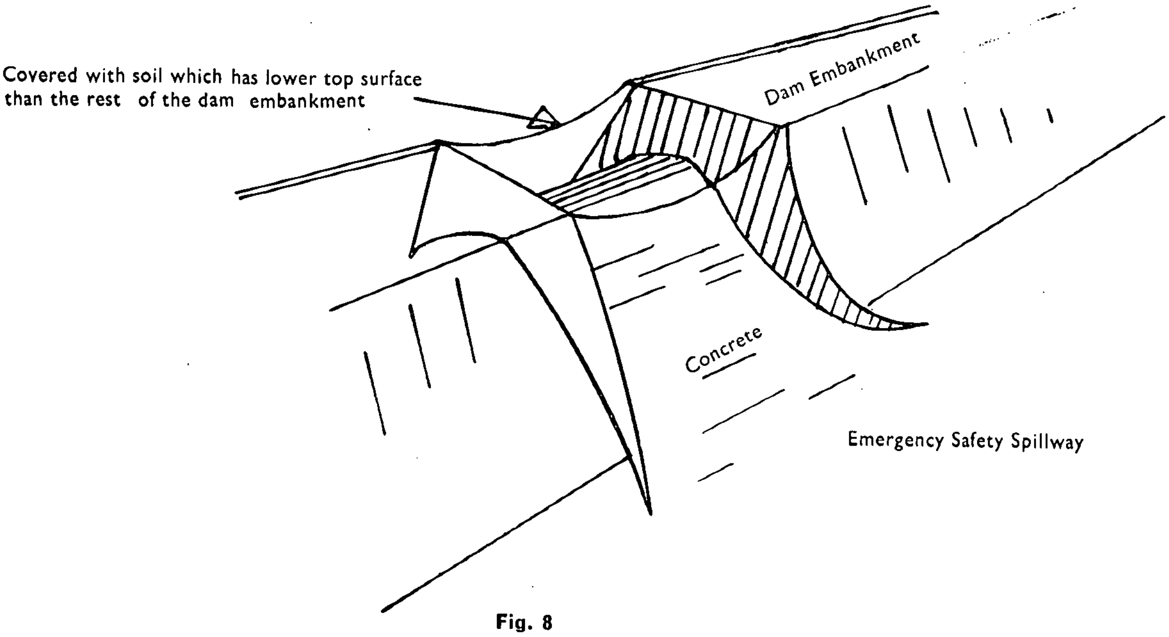
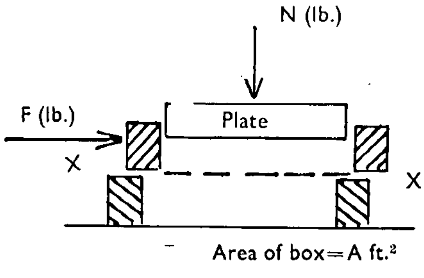


Fig. 8
Note: Slopes drawn above are steeper than actual slopes



Shear Box

Fig. 8a

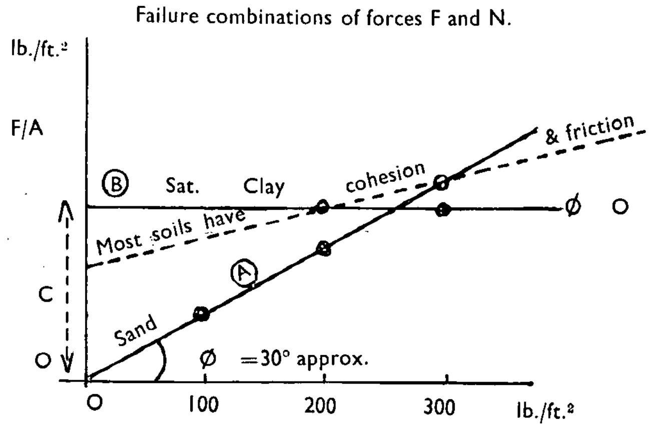
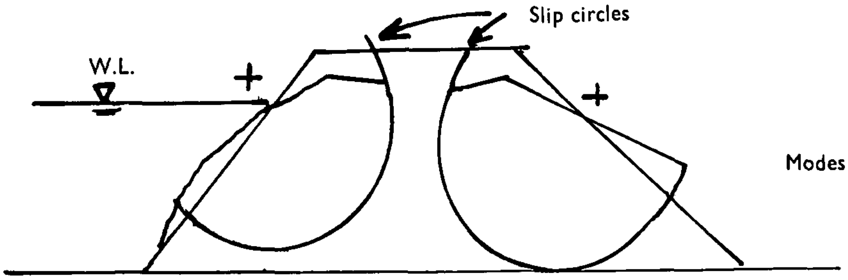


Fig. 8b



Modes of failure of most slopes

Fig. 9a

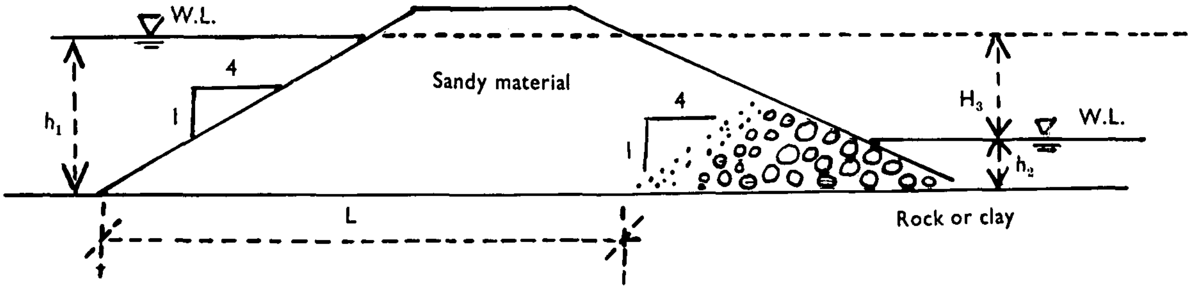


Fig. 9b

Estimation of seepage through dam. The construction of flow nets is the easiest method (see Ref. 6). However for certain dams such as that shown above formula can be derived, e.g.

Seepage (per ft. length of dam into paper) is —

$$q = \frac{k}{.8004}\left[X + \sqrt{Y^2 + .8004\,(h_1^2 - h_2^2)}\right] \text{ cu. ft. per sec. per ft. width}$$

where k = coeff. of permeability of sandy matl (ft./sec.)

and $X = (3.604\,h_1 - .396h_2 - L)$ feet

The value of k is found in a permeability test.

The chart in Fig. 10 may be used to check both the upstream and downstream slopes providing these slopes are 1 to 3. The value of F will indicate whether flatter slopes are required.

The root systems of grasses planted on the slopes will assist slope stability by decreasing the water pressures in the dam. Dams less than 10 ft. high do not require special compaction equipment.

Stability of Road Embankments

The stability of a large road embankment with a slope of 1 to 3 can also be checked by using Fig. 10. This would correspond to finding the factor of safety F for a bank subjected to prolonged soaking rains. Other charts must be used if the slope is not 1 to 3.

Most of the previous comments can be applied to road embankments.

Stability of Natural Slopes

Most natural slopes can be regarded as infinite slopes.

If no seepage occurs from the slope the factor of safety F can be found as follows:

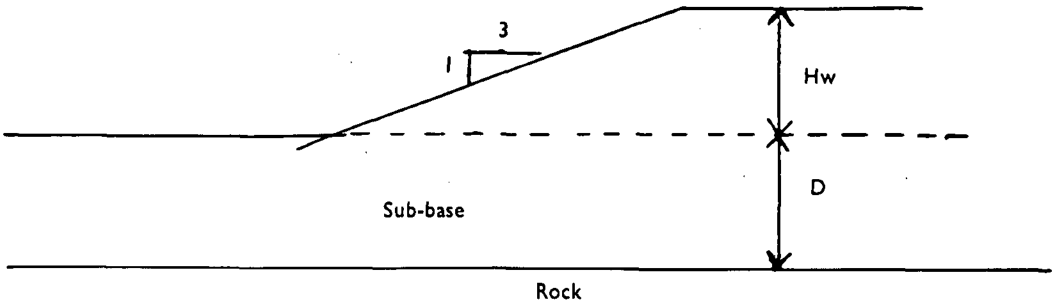
For sands: $F = \tan\phi/\tan\beta$ .. .. .. (4)

where β = angle of the slope.

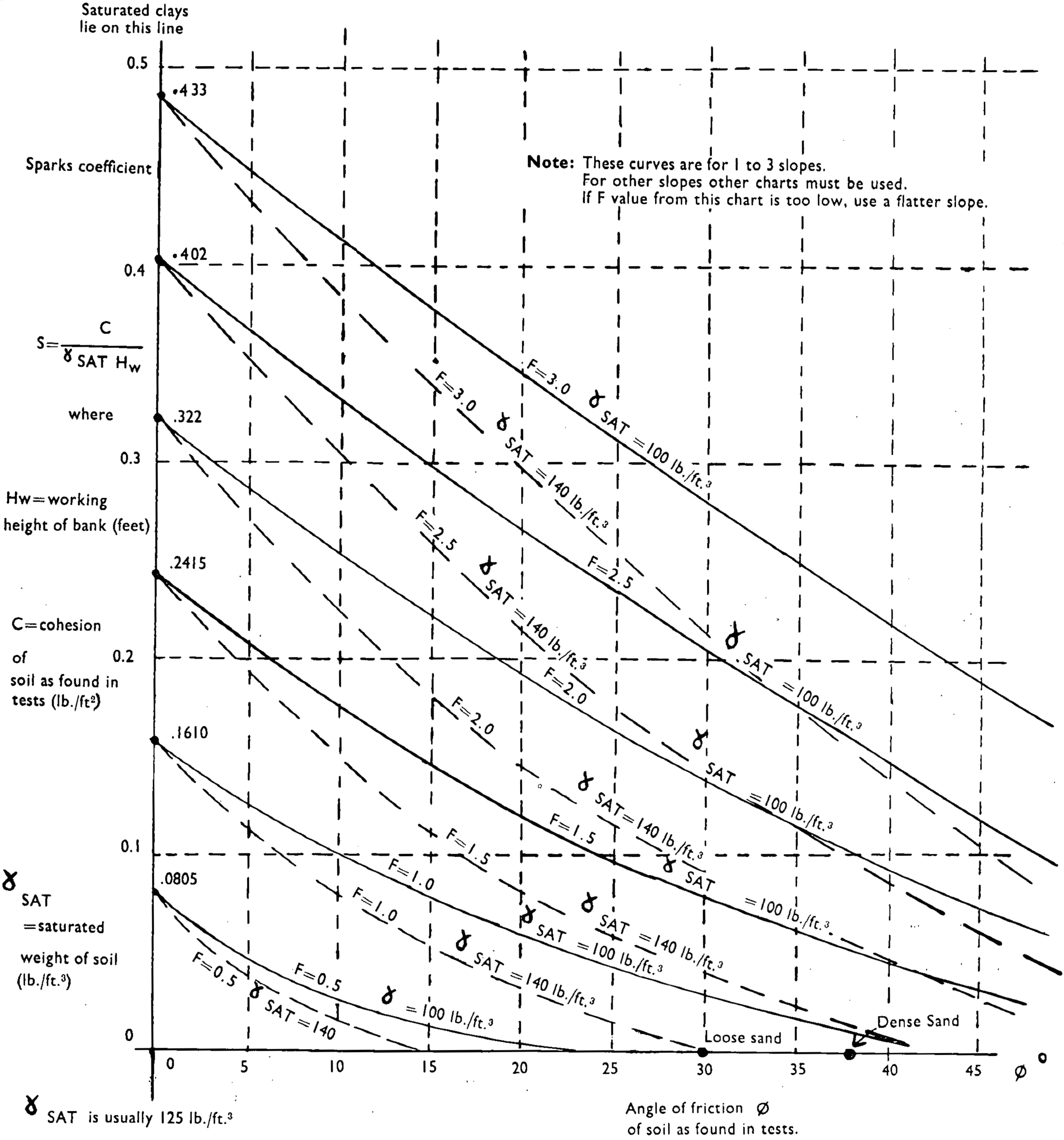
For clays: $F = \dfrac{c\,(1 - \cos\theta)}{0.230.d.\gamma.\sin\beta}$ .. .. .. (5)

where θ is approximately 75 degrees, and d is the thickness of the clay overlying bedrock (see Fig. 11).

Curves for draw-down state (upstream slope)
or **constant rain on embankment** (downstream slope)



These curves will be safe for cases where depth D of sub-base is equal to, or less than H_W; providing the sub-base material is the same or stronger than material in bank. Enter chart with known values of c, γ_{SAT}, H_W, ϕ to find F.



Note: These curves are for 1 to 3 slopes.
For other slopes other charts must be used.
If F value from this chart is too low, use a flatter slope.

γ SAT is usually 125 lb./ft.³

Fig. 10

Before the construction of a dam, the owner should investigate his water rights and those of his neighbours. Where necessary he should make written arrangements with his neighbours.

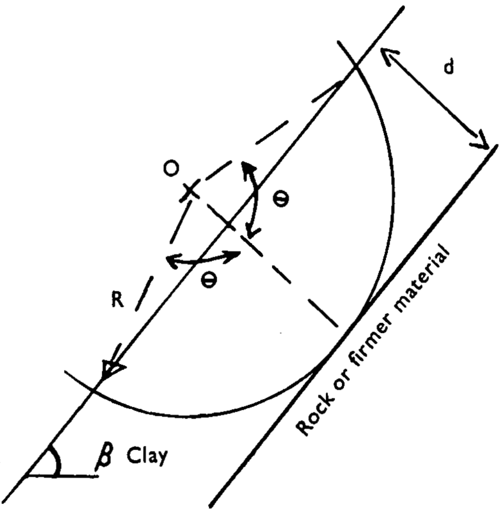
In particular the owner should investigate the possible implications of a failure of his dam. Larger factors of safety may be necessary for dams constructed above inhabited areas.

The overflooding of diversion canals on to lower cultivated fields might cause damage to a neighbour's crops. The location of erodable earthworks above a neighbour's dam might result in the silting-up of the neighbour's dam unless suitable precautions are taken.

Fig. 10

For **Fig. 10** see separate sheet.

Fig. 11



Stability of natural slopes.

APPENDIX I

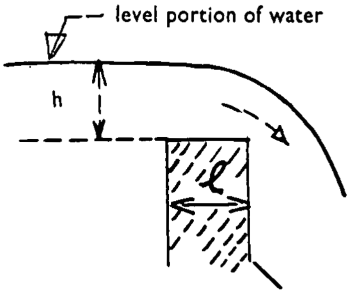
Notes on Spillways

1. Sharp crested weirs (i.e. rectangular shape)
Rate of flow over weir is —

$Q = 3.3 \times B \times (h)1.5$ cubic ft. per sec.
where B = breadth of weir (feet)
h = water level height above weir (ft.)

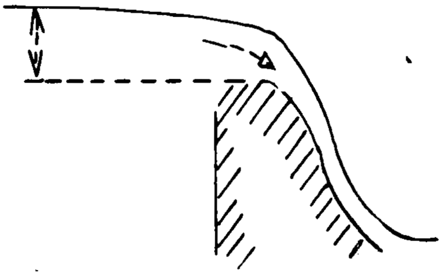
If l is less than, or equal to $4 \times h$ use the above formula. If l is greater than $4 \times h$ use coefficient 3.0 instead of 3.3.

The channel slope below weir is usually steeper than the critical slope for critical flow, and hence has no effect on above formula.



2. Ogee spillway

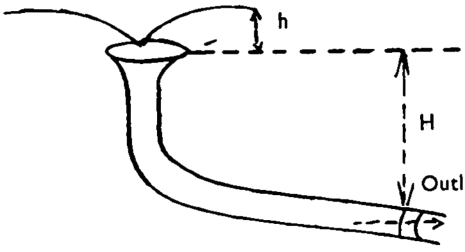
This is specially shaped according to a mathematical formula. The coefficient in the above formula is now 4.0 and can increase to 4.5 as h increases, at which stage the water breaks clear of spillway and one must return to formula for sharp crested weir.



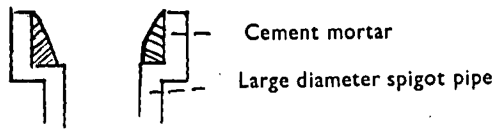
3. Circular bellmouth spillway

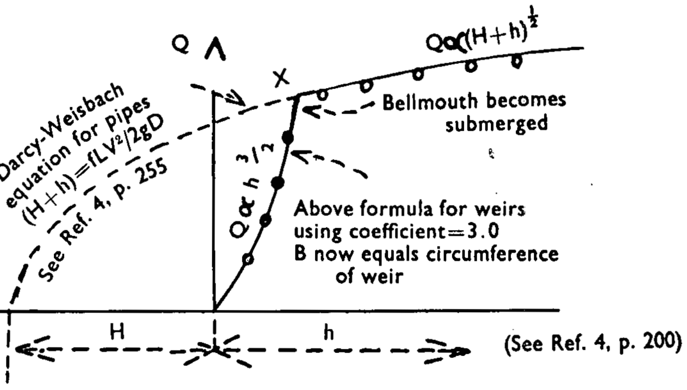
Advantage — water is not passing over embankment. Disadvantage — when inlet becomes submerged the rate of discharge hardly increases.

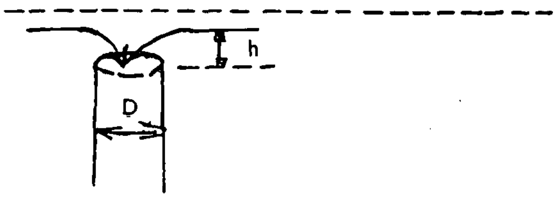
Floating booms are required to prevent debris clogging pipe. Radiating fins are required around weir to prevent vortex formation which reduces flow.



Suggestion:







4. *Circular shaft spillway* (similar to above bellmouth theory).

Gourley (Ref. 5) found that $Q=c_1.L.h1.42$ where c_1 varies 2.93 to 3.03. L=circumference (ft.)

For each 2″ increase in diameter from 8 to 30 ins. add 0.01 to 2.93 to obtain c_1 value. Use 3.06, 3.09, 3.12 for 40″, 50″, 60″ diam.

Conclusion

In conclusion the author wishes to draw the attention of the reader to possible legal problems which might arise due to the construction of earthworks.

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Note: The author has developed a nomogram-chart for determining the value of Q in equation (3).
The above paper does not deal with the use of flow nets for the estimation of seepage losses through the earth dam.