Jean Kerisel

The Stability of the Upstream Slope of Earth Dams

by Erling Reinius

Fontanelli

Taipei '67

The Stability of the Upstream Slope of Earth Dams

By Erling Reinius

Professor of Hydraulic Engineering,
Chalmers Institute of Technology, Gothenburg, Sweden.
Consulting Engineer of Vattenbyggnadsbyrån (VBB).

Contents

Symbols

A = area, m^2
a = length, m
b = thickness of slope protection, m
C = resultant cohesion, tons (of 1 000 kg)
c = cohesion in Coulomb's equation, tons/m^2
c_r = required cohesion, tons/m^2
c_v = coefficient of specific compression of soil, m^2/tons
D = depth of the water above the toe of the dam, m
E = modulus of elasticity, tons/m^2
E = voltage drop, volts
e = void ratio = volume of voids per unit of volume of solid soil constituents
F = total internal friction force, tons
f = friction force per unit of area, tons/m^2
g = acceleration of gravity, m/sec^2
H = height of slope, m
h = piezometric head, m
h_c = height of capillary rise, m
I = hydraulic gradient, m per m
I = electric current, amp.
K = correction factor for the friction circle method
k = coefficient of permeability (Darcy's coefficient), m/sec
l = length, m
M = moment, tons.m
m = mass, tons/m/sec^2
n = porosity = ratio between total volume of voids and total volume of soil
P = force, tons
P = hydrostatic pressure on the slope surface, tons
p = normal pressure per unit of area, tons/m^2
Q = discharge, m^3/sec
R = total resultant force, tons
R = electric resistance, ohms
r = radius of circular sliding surface
r_f = radius of friction circle

S = safety factor
s = shearing strength, tons/m^2
T = time, sec
t = time, sec
U = internal hydrostatic pressure (uplift), tons
V = volume, m^3
v = discharge velocity, m/sec
v_n = net velocity of percolation water, m/sec
v_w = velocity of lowering of the water level in the reservoir, m/sec
W = total weight, tons
α = half of central angle
β = angle of slope inclination
γ = unit weight of soil, tons/m^3
γ_w = unit weight of water, tons/m^3 (= 1.0)
γ_b = unit weight of slope protection, excluding the pore-water, tons/m^3
γ_{bw} = unit weight of slope protection, including the pore-water, tons/m^3
$\varkappa$ = coefficient of compressibility of water, m^2/ton
φ = angle of internal friction at failure, degrees
φ_r = required angle of internal friction, degrees

Inclinations of slopes are given as the ratio between the vertical height and the horizontal distance.

I. Synopsis

The most common type of dam is, no doubt, the earth dam, the heights of which vary from something very low up to about 140 metres. The latter height will be reached by the Anderson Ranch Dam, now under construction in the United States. The earth dam is often inexpensive and especially suitable on soil foundations.

Up to the last few decades the dimensions of earth dams have been determined on empirical principles only. Such dimensions and slopes have been chosen as, from experience obtained from other dams, were considered to be sufficient to prevent earth slides. In spite of this, numerous failures of earth dams have occurred, with the consequence that the earth dam, as compared with the concrete dam, has often been regarded with a certain distrust.

Even nowadays earth dams are sometimes designed on empirical principles, in spite of the fact that the rapid development of soil mechanics has resulted in more scientific methods for their designing.

This thesis deals with the problems of the designing of the upstream part of an earth dam, especially when the dam is provided with a watertight core, e. g. as a central core-wall, supported by fills of cohesionless materials such as sand or gravel.

For the theoretical treatment of these problems many simplifying assumptions have to be made. For instance, it must be assumed that the soil is homogeneous. Owing to this circumstance the computations are not fully applicable to dams actually constructed. This should be borne in mind when applying the results of the computations.

One of the most important of the factors which cause stresses in the upstream part of an earth dam is the pore-water pressure. Its magnitude has been determined by the author both at rapid and at slow drawdowns of the water level in the reservoir, and a number of figures have been drawn illustrating flow nets in cases where the foundation is either impervious or has the same permeability as the embankment fill.

By making use of the circular arc method formulas have been established for calculating the effect which the weight of the soil, the external water load, the internal pore-water pressure, and the slope protection, exercise on stability. It has been assumed, for this purpose, that the sliding surface is located exclusively on the upstream side of the central core. When the water level in the reservoir is lowered, great local stresses arise where the water level intersects the surface of the slope. Parts of the slope may therefore be less stable than the entire slope. The thinner and lighter the facing of the slope, the more pronounced is this effect. If, owing to its weight, the facing is to have a favourable effect on the stability of the slope, it is necessary that, at the drawdown of the reservoir, the facing and the filter underneath shall be able to divert the water flowing out of the fill, without the filter being completely saturated with water.

The stability increases if the facing is designed and constructed in such a way that it can take pressure parallel to the surface of the slope and that this pressure can be transferred to the foundation. In such a case the friction arising between the facing and the sliding soil segment below the facing contributes to increasing the stability.

Another measure serving to increase stability consists in reducing the pore-water pressure by means of horizontal filter layers of coarse material or something similar.

In order to examine the accuracy of the methods of computation, as well as the utility of the suggestions for increasing stability, tests with models built of sand have been made by the author on a relatively large scale. By allowing water to flow over the face of the slope the capillary forces were eliminated, and the transient stress conditions occurring after a rapid drawdown appeared in the model as permanent stress conditions, which could be studied in detail; at the same time the pore-water pressure could be measured. The conformity between the results of these tests on models and the theoretical computations by means of circular sliding surfaces is satisfactory.

In conclusion, rules of designing are discussed, and examples are given of the economical design of the upstream portion of an earth dam by the aid of the diagrams supplied. Certain safety factors which are dependent on the reliability of the assumptions made, have also been introduced.

II. Various Kinds of Dam Failures

In the course of time many failures and slides have occurred in earth dams; a great number of these have been recorded in the technical literature, and surveys of dam failures have been made (JUSTIN 1923, 1932; SCHATZ and BOESTEN 1936; CREAGER, JUSTIN and HINDS 1945; BLOMQVIST [not published]). On the basis of such descriptions of 121 different failures of earth dams, which have occurred in this century and, in some cases, at the end of last century, the following causes of earth dam failures have been established.

1. Owerflowing of the crest, followed by erosion (36 failures).
2. Leakage through the dam or the foundation (25 failures).
3. Leakage from or along pipes or culverts in the dam (23 failures).
4. Interior water pressure in hydraulic fill dams, followed by slides (10 failures during construction).
5. Insufficient dimensions causing slides on the slopes (9 failures).
6. Insufficient compaction, the subsequent settling causing cracks and fractures (6 failures).
7. Foundation slides (3 failures).
8. Leakage through the dam due to animals (2 failures).
9. No special cause stated (7 failures).

Evidently the 121 failures thus studied do not comprise all that have occurred. Many failures have not even been recorded in the literature, while others may have been overlooked. The above list of causes of earth dam failures shows, however, what circumstances should be particularly taken into account when designing and constructing an earth dam.

First of all, it should be remembered that running water has a capability of carrying away soil particles and that, if water gets an opportunity of doing so, the removal of these particles is accelerated by the successive widening or shortening of the waterway. Sooner or later this will cause erosion, piping, slides or dam failures — items 1, 2, 3, 6 and 8 above. In the designing of an earth dam, the crest should therefore be located so high, and the spillways should be so large, that the probability of overflowing is almost nil. Further, leakage through or under the dam must be prevented to the extent deemed possible and suitable, and leakage water, if any, must be drained away, in order to avoid piping and damage.