LOADS ON EARTH-FILL AND ROCK-FILL DAMS ARISING FROM WATER AND WIND

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Contents

Summary

This article deals with two fundamental design conditions with which earth embankments forming impoundments for storing water have to comply. The first is to withstand the seepage forces especially at the downstream toe of a dam, and the other is to be able to resist wave attack on the upstream slope.

Seepage forces are readily analyzed by means of flow nets from which pore pressures are derived and escape gradients on the downstream slope determined. The design of core walls, downstream filters, and drainage layers follows.

Upstream slope protection is designed according to stability parameters against calculated wave heights and runup. The rock size of the protected layers is a function of the maximum wave for a given wind stress and exposure condition. Empirical formulas are given for the calculation of stable rock size and for the height of runup due to wave and wind tide action. The latter determines the dry freeboard allowance to be added to the embankment height.

1. Introduction

Water in the reservoir constitutes the basic load and generates the effects that may inflict damage or, at worst, ultimate failure of the dam. In addition come body forces due to embankment weight and potential earthquake loads. The water head imposes external loads acting on the impervious element, and submerged fills are subjected to uplift. Flow through the dam and adjacent ground sets up pore pressures and seepage forces acting internally, and waves exert loads on the upstream slope of the dam (see *Construction of Small Earth-Fill Dams* and *Large Dams*).

2. Calculation of Loads, Forces, and Dimensions Involved

The loads and forces due to seepage influence the stability of the main body of the embankment and may cause erosion and instability at the toe of the embankment. To deal with the first aspect, the free surface or the phreatic flow line has to be depressed as low as possible in the downstream shoulder of the embankment, otherwise it may induce slope failure. The second matter is dealt with by building in filters and drainage layers to concentrate the exit flow gradient of seepage at the suitably designed toe. These two processes are now described in detail.

2.1. Seepage Forces and Pore Pressures

Versatile finite element modeling and numerical analyses may be applied to compute steady state and transient pore pressures and seepage forces in an embankment dam and its foundation. However, so far in design practice, the method of flow nets has mainly been used, as even an approximate flow net may give the designer a good appreciation of the flow situation. A flow net is a two-dimensional, graphic representation of the hydraulic condition and is composed of two sets of curves: equipotential lines and flow lines. Equipotential lines designate points of equal potential. For laminar flow, the potential at any point is the sum of the elevation of the point above a reference level and the actual pore pressure at the point, expressed in terms of the piezometric height, i.e. the water column above the point. Hence, the equipotential lines join points in the profile for which the piezometric elevation is the same, as may be seen in Figure 1.

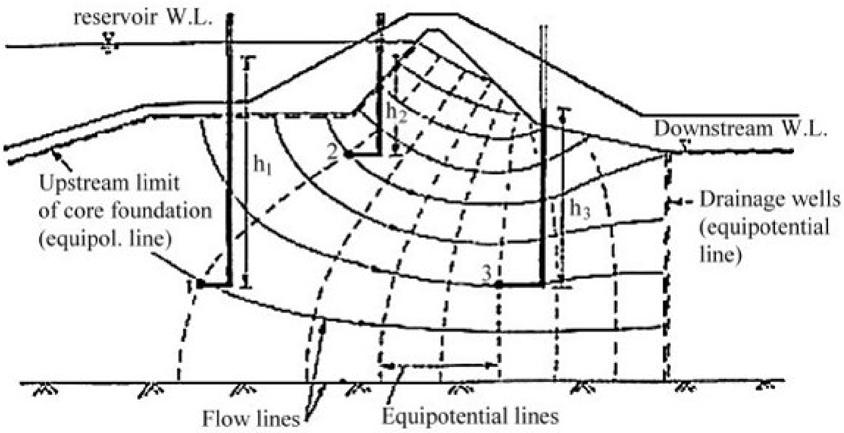

Figure 1. Typical flow net for an embankment dam.Core and foundation are assumed to have the same permeability properties.

The flow lines depict the direction of flow paths through the profile. The area between two adjacent flow lines represents a flow channel. A flow net may be produced on the basis of analytical computations, by means of physical models or analog computers, or, most often, graphically by hand sketching. The computer can also convert numerical values from finite element analysis into graphical flow nets, simplifying the interpretation of results.

Under isotropic conditions, i.e., the same permeability in all directions, the equipotential lines and the flow lines will intersect each other orthogonally. In practice, the flow net is formed such that the drop in potential from every equipotential line to the next is constant, and each flow channel transports an equal amount of water. These preconditions imply a constant ratio between length and width of each "rectangle" in the flow net as shown in Figure 1.

When drawing flow nets, it is first essential to fix the equipotential lines and flow lines given by the boundary conditions. Thus in Figure 1, the flow line along a boundary of watertight rock as well as the equipotential line along the upstream boundary of the impervious core are given. Likewise, the downstream drainage well, which is under hydrostatic pressure, represents an equipotential line. The fact that flow lines and equipotential lines in Figure 1 appear in equal numbers is purely incidental.

By definition, the potential and pore pressure at any point in the section can be determined from the flow net. Hence, the average gradients of flow from one point to another inside the mesh can be determined by measuring the distance between them. The average gradient is defined as the ratio of potential difference to corresponding flow path length.

The drop in potential corresponds to the energy lost over the flow distance between the points. This energy is transferred by friction to the particle matrix through which the water flows, generating a so-called seepage force acting in the direction of the flow. The seepage force per unit volume of the particle matrix is proportional to the flow gradient and the unit weight of water:

$$j = i \cdot \gamma_w \qquad (1)$$

where i : hydraulic gradient (non-dimensional)
γ_w: unit weight of water

The seepage force exerts an effective pressure in the direction of the flow line and creates internal stresses that must be added to the effective stresses of the no-flow hydrostatic situation. This is an important principle described for a simple case below.

Figure 2 illustrates a situation with vertical, upward exit flow downstream from the embankment toe. In a point at depth, z, below the ground surface, a pore pressure, $u = \gamma_w(z + \Delta h)$, exists. The free-water level is assumed to be at ground level. The potential drop over the distance, z, equals Δh and the average gradient $i = \Delta h/z$.

The vertical effective stress at the same point in the no-flow hydrostatic state is $\gamma' z$, where γ' is the submerged unit weight of the material. As the seepage force here acts in the opposite direction of the gravity force, it must be subtracted, and the resulting effective stress at the point in the state of flow becomes:

$$\sigma' = \gamma' z - i\gamma_w z = \gamma' z - \gamma_w \Delta h \qquad (2)$$

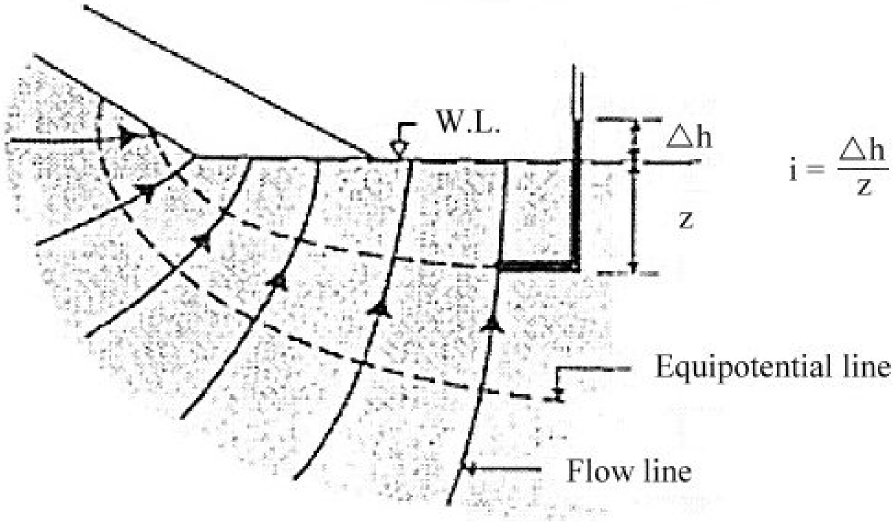

Figure 2. Example of flow net determination of exit gradient. To determine the effective stress situation, use submerged unit weight combined with seepage forces *or* total unit weight combined with pore pressures determined from the flow net.

Alternatively, the effective stress may be calculated as the difference between total stress and pore pressure at any point:

$$\sigma' = \sigma - u = \gamma_z - \gamma_w(z + \Delta h) = \gamma' z - \gamma_w \Delta h \qquad (3)$$

From this equation, the so-called critical vertical gradient, i_c, at which effective stress at the point would be zero, and at which material particles would become suspended in water, is determined.

$$i_c = \frac{\gamma'}{\gamma_w} \qquad (4)$$

To prevent this unstable situation from occurring, the ground surface downstream should be loaded with an inverted filter, which increases the effective stresses beneath the surface and stops the erosion and piping.

From a flow net, pore pressures and seepage forces needed for embankment deformation and stability analyses can be determined. The quantity of seepage through the core can also be calculated by means of a flow net.

2.2. Outflow Forces at Dam Toe

Under normal operating conditions, the downstream supporting fill and toe of the dam will not be exposed to seepage forces and often no requirements are specified for the drainage capacity of the dam. Ample drainage capacity is, however, essential for the safety of the dam if overtopping or big leaks should accidentally occur. This situation must be studied and constitutes a part of the overall risk analysis for the dam.

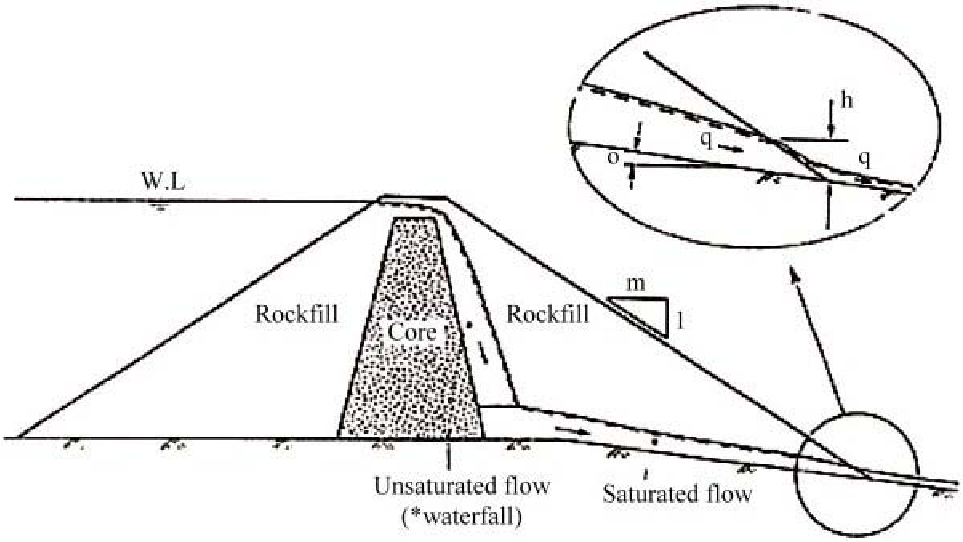

Figure 3. Outflow of water at the toe of the dam

Outflow of water at the toe of the dam is sketched in Figure 3. Depending on runoff intensity, the water may exit on the slope at a certain level above the base determined by the permeability of the fill. The fill is subjected to seepage forces and pore water pressures that reduce the stability along potential sliding planes inside the fill. The overflowed part of the slope is further exposed to surface unraveling and erosion stone by stone. Flow through coarse rock fills will generally be turbulent. The flow velocity is calculated as being:

$$v = \sqrt{k_t i} \tag{5}$$

where v : discharge velocity
k_t : permeability at turbulent flow (e.g. m^2/s^2)
i : hydraulic gradient (non-dimensional)

The turbulent permeability may roughly be estimated from the equation:

$$k_t = \frac{1}{\beta_o} \cdot \frac{n^3}{(1-n)} \cdot g d_t \tag{6}$$

where β_o : grain shape factor (β_o = 3.6 for quarried rock)
n : porosity of the fill
g : acceleration of gravity size
d_t : significant particle size

In well-graded materials, the significant particle size is approximated by d_t = 1.7 d_{10}. For narrowly graded materials d_t = d_{50} is similarly used. The sieve opening diameters,

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Bibliography

Bruun P., ed. (1985). *Design and Construction of Mounds for Breakwater and Coastal Protection,* 938 pp. Amsterdam: Elsevier. [Standard reference.]

Cedergren H.R. (1989). *Seepage, Drainage and Flow Nets,* Third Edition, 456 pp. New York: Wiley. [Thorough treatment.]

International Commission on Large Dams (1990). *Dispersive Soils in Embankment Dams,* 53 pp. ICOLD Bulletin 77. Paris: ICOLD. [A detailed account with case studies and guidelines.]

International Commission on Large Dams (1992). *Bitumen Cores for Fill Dams,* 91 pp. ICOLD Bulletin 84. Paris: ICOLD. [The use of bitumen as a watertight cutoff material in earth dams.]

Kjærnsli B., Valstad T. and Höeg K. (1992). Rock-fill Dams, Design and Construction. *Hydropower Development* **Vol. 10**, 53–62. Norway: Norwegian Institute of Technology, Division of Hydraulic Engineering. [The basis of this article.]

Penman A.D.M. (1982). *Materials and Construction Methods for Embankment Dams and Cofferdams* (General Report, Question 55, 14th ICOLD Congress, Rio de Janeiro), Volume 4, pp. 1105–1228. [Thorough review of the state of the art.]

Pilarczyk K.W. (1990). *Design of Seawalls and Dikes—Including Overview of Revetments*, *Coastal Protection* (Proceedings of Short Course, Delft University), pp. 197–228. Rotterdam: Balkema. [Valuable reference for the practicing coastal engineer.]

Saville T. Jr., McClendom E.W., and Cochran A.L. (1962). *Freeboard Allowance for Waves in Inland Reservoirs* (Proceedings of the American Society of Civil Engineers) **Vol. 88**, No. WW2, pp. 93–124. [Much referred to keynote paper on wind-generated waves in reservoirs.]

Sherard J.L., Woodward R.J., Gizienski S.F. and Clevenger W.A. (1963). *Earth and Earth-Rock Dams; Engineering Problems of Design and Construction*, 725 pp. New York: Wiley. [Early reference volume.]

Solvik O. and Svee R. (1976). *Flow Condition Criteria and Some Through-Flow Problems in Rock-Fill* (Proceedings of the 12th ICOLD Congress, Mexico), Vol. 2, pp. 637–646. [Case studies and their interpretation.]

Stephenson D. (1979). *Rockfill in Hydraulic Engineering*, 215 pp. Amsterdam: Elsevier. [Standard reference work, one of a series of handbooks.]

Thomsen A.L., Wolt P.E., and Harrison A.S. (1972). *Rip-Rap Stability on Earth Embankments Tested in Large- and Small-scale Wave Tanks*, Technical Memorandum No. 37, 115 pp. Washington, DC, US: US Army Corps of Engineers, Coastal Engineering Research Center. [Practical model-testing data.]

Van der Meer J.W. (1987). Stability of Breakwater Armor Layers—Design Formulae. *Journal of Coastal Engineering* 11, 219–239. [Useful designer's guideline.]

Biographical Sketches

Björn Kjaernsli received his academic training at the Eidgenössische Hochschule (Dipl. Ing., 1949) and the Imperial College of Science Technology and Medicine, London (1953). He was stationed at the Norwegian Geotechnical Institute (NGI) since its establishment in 1952, and he headed its Dam and Rock Engineering Division throughout the period 1957 to 1988. He is internationally recognized for his work in dam engineering and hydropower development.

Tore Valstad received his degree in civil engineering at the Norwegian Institute of Technology (1967) and M.Sc. from the University of California, Berkeley (1982). He has been with the Norwegian Geotechnical Institute (NGI) from 1967 on. This period was interrupted by his UNDP assignment as chief technical advisor in India from 1985 to 1986. Since 1986 he has held the position of special technical adviser at NGI, with emphasis on dam and rock engineering.

Kaare Höeg received his civil engineering degrees from the Massachusetts Institute of Technology (Sc.D., 1965), where he was assistant professor during the period 1965 to 1967. He then joined the faculty at Stanford University in 1968 and was appointed full professor in 1973. He was director of the Norwegian Geotechnical Institute (NGI) from 1974 to 1991 and now holds the position of special adviser at NGI and professor at the University of Oslo, Norway.
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