Probabilistic safety evaluation of earth dams

L'évaluation probabiliste de la sécurité des grands barrages

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SYNOPSIS: A probabilistic approach for the evaluation of the safety of existing dams is discussed. The modes of failure dealt with are erosion due to overtopping, erosion due to piping and slope instability. The probability of failure is assessed by determining the probability of the demands (loads) exceeding the resistance (capacity).

The probability for a failure due to overtopping is determined by expressing the demands in terms of an EROSION POTENTIAL of the overtopping hydrograph and the resistance of the embankment by means of the EROSION RESISTANCE. A similar procedure is envisaged for the calculation of the probability due to piping.

The probability of slope instability is determined by means of failure domains for critical sections. By assigning probabilities to several intermediate "domains" between an upper and lower limit for failure in terms of cohesion and angle of friction, a total probability of failure due to slope instability can be determined.

INTRODUCTION

Probabilities of failure are an important component in risk analyses performed to evaluate the safety of existing dams and, to a lesser extent, in feasibility studies. This paper briefly presents the methodology for the estimation of failure of earth dams and suggests some improvements. As the methodology was (intentionally) developed step-wise starting from the "known" deterministic approach, this approach will be reviewed first.

DETERMINISTIC APPROACH

The deterministic approach is based on criteria such as required factors of safety for slope stability calculations etc. Spillway capacities are likewise determined using prescribed criteria. Material parameters and flood frequencies are usually treated in a deterministic fashion i.e. these values are used as fixed or point values instead of probability density functions.

Although adequate factors of safety have apparently been used in the past, several earth dams failed. Insufficient spillway capacity is the main cause of failure, while piping and slope instability (sliding) failures occur less frequently. This implies not only that any reasonable design has a finite chance of failure but also that no structure is "fail safe". The main disadvantage of the deterministic approach is that it is unable to give a clear indication of the risk involved. The use of probability theory may not necessarily reduce failures but will definitely provide a better understanding of the risks involved. This will prove useful for feasibility studies and for the evaluation of the safety of the structure.

PROBABILISTIC EVALUATION METHOD

General

The probability of failure and the potential damage associated with such a failure are the cornerstones of a risk-based evaluation.

Various failure modes for embankment dams have been identified, of which excessive erosion, owing either to overtopping or to piping, and slope failure are the most important. Of these, the probability of external erosion and slope instability can be reasonably estimated in a semi-analytical way at present. Other failure modes like piping can to some extent be estimated only subjectively. The potential damage can be expressed in terms of lives lost, and economic and socio-economic losses. Methods used to estimate the probability of failure due to external erosion and slope instability have been presented in Knoesen, Oosthuizen and Van der Spuy (1988). These methods as well as suggested improvements are discussed in the following paragraphs. A paragraph on the evaluation of risk is also included

The methods of analyses presented below, follow the "Loads (Demands) - Resistance (Capacity) - Response" philosophy as proposed by amongst others Oosthuizen (1985). Possible load-scenarios (Demands) on the structure are predicted. The structure offers a Resistance to these loads which needs to be quantified probabilistically. The probability of failure is then represented by the probability of demands exceeding the resistance.

The Loads on an embankment dam can be classified as normal and extreme loads. Normal loads like pore pressures play a major role in failure modes like piping and slope instability. For the analysis of extreme loads like floods and earthquakes, a relationship between the magnitude and probability of occurrence is required. In contrast to practices in countries prone to earthquakes, seismic loads are considered to be of secondary importance in South Africa.

The Resistance capacity of the structure is governed by several factors, such as foundation properties, nature of the material used for the wall, geometry, as well as quality of design, construction, maintenance and operation. Many of these are difficult to quantify while the properties of the materials may be so uncertain that large coefficients of variation have to be used.

In the Response analysis a comprehensive model, using for example multivariate distributions, can be compiled. Fault and event trees are used to identity the governing factors for a particular analysis. The high degree of uncertainty in the estimation of reasonable parameters (and their distributions) does not however warrant extensive analytical procedures. Simplified methods are therefore used in practice.

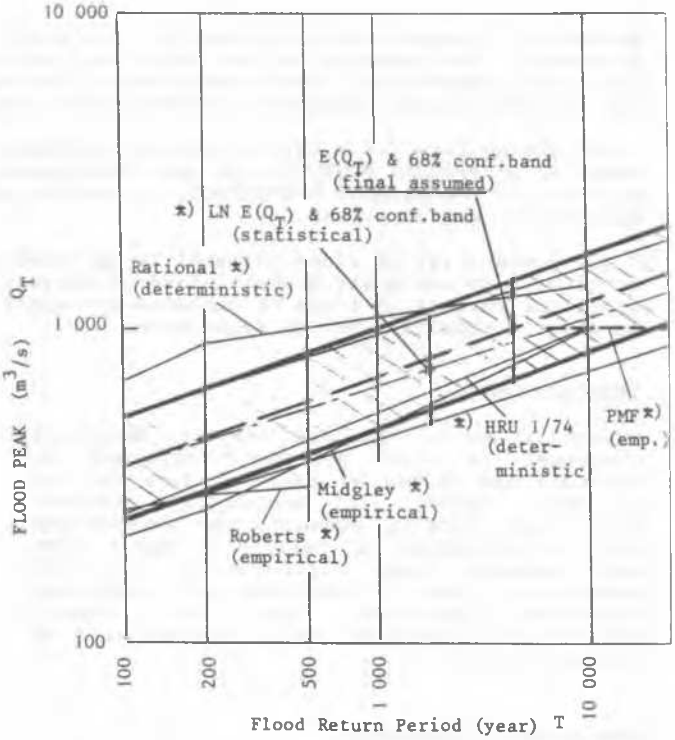
Overtopping (external erosion) as mode of failure

Overtopping has been the cause for approximately a third of all the recorded earth dam failures worldwide (Serafim and Cavilhas: 1984). It is therefore of major importance. This mode of failure results from the water level in the reservoir rising sufficiently high to cause the water to flow (continuously or intermittently) over the crest thereby causing the embankment to erode sufficiently to form a breach.

The DEMAND on the structure can be represented by the rise in water level which in turn is influenced by flood magnitude, wind action, spillway and outlet capacity and flood retention capacity of the reservoir.

Floods cause a rise in water level of the reservoir when the inflow exceeds the outflow. A short duration sudden increase in outflow peak may however be caused by a steep-fronted flood and a favourable reservoir geometry, according to Kovacs et al (1984). Since the simultaneous occurrence of extreme floods and winds is fairly unlikely, the effect of wind is not considered when evaluating the safety of a dam.

The probability distribution of the flood magnitude should ideally be estimated from statistical records. These records are usually too short (or non-existent) to estimate extreme floods with an acceptable degree of accuracy. Statistic, deterministic and empirical methods are available to estimate the magnitude of these extreme floods, confidence intervals, and the shape of the flood hydrograph. Figure 1 gives a typical example how the mean flood magnitude and upper and lower limits can be estimated. As both the height and duration of overtopping are important, the probability of the flood volume is as important as the flood peak. The Runhydrograph method (see figure 2) proposed by Hiemstra and Francis (1979) proved to be useful in this respect.



*)As described in HYDRO (1982)

FIGURE 1: Flood distribution variation.

The retention of the flood is influenced by the initial level of the reservoir. The variation of this initial water level can be estimated from the past records or from the planned future operation. In the case of a gated spillway or outlet structure of size, the reliability thereof should also be considered. Possible gate-malfunction or -operation should be incorporated in the estimation of the spillway effectiveness.

The RESISTANCE of the structure is determined by the geometry and material comprising the embankment. Evidence suggests that an embankment can resist a significant amount of overtopping before an actual breach occurs. This is also documented by amongst others Ponce and Tsivoglu (1981), Fread (1985) and Powledge and Sveum (1987). Resistance to erosion is offered by the slope

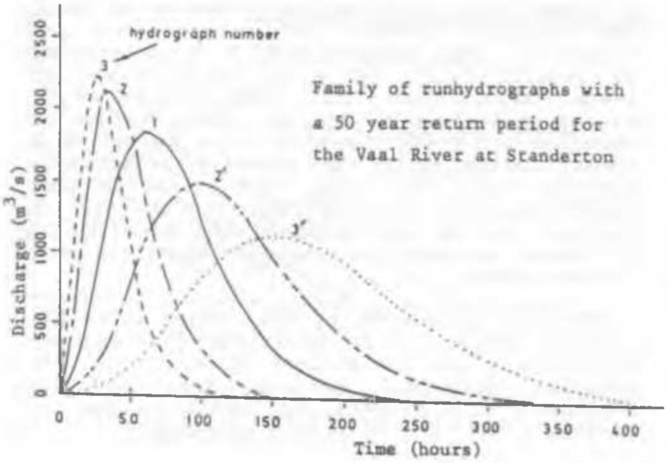


FIGURE 2: Family of hydrographs (from Hiemstra and Francis (1979)).

protection (like grass or rock protection) and the material of the embankment (usually cohesive). A study of relevant literature (Knoesen and Oosthuizen: 1985) concluded that, due to the gradual erosion process, the erosion is affected by both the height and the duration of overtopping. Preliminary investigations indicate a hyperbolic relationship between the critical height and the duration of overtopping for a given embankment geometry and type of material. The height and duration of overtopping caused by a flood represent the Erosion Potential EP (Demand) on the wall. The geometry and material of the wall determine the Erosion Resistance ER (Capacity) of the wall. Preliminary assumptions, very similar to those of Fread (1985), lead to a threefold flow concentration in a gully. The approximated relationships represented in equations (1) and (2) were deduced from these assumptions:

$$EP = H^{\beta}.t \qquad (m^{\beta}.\,hour) \qquad (1)$$

$$ER = Coeff.\ T/Ce \qquad (m^{\beta}.\,hour) \qquad (2)$$

Where EP = Erosion Potential
ER = Erosion Resistance
H = Mean water head above crest (m)
t = Duration of overtopping (hours)
β = Exponent ranging from 0,6 to 0,8
T = Topwidth (m)

Coeff. = 7.E-8 (m^{β}. hour/Pa-sec)
E = Exponential (base 10); and
Ce = Erosion coefficient of earthfill

Where Ce = E-7 m/s/Pa ($\approx$ 1.E-4 g/dyne-min - see Arulanandan and Perry (1983)) for a highly erosion resistant cohesive earthfill
and = ∞ for negligible erosion resistance like a sandy material

A similar hyperbolic relationship between height and duration of overtopping can be derived for a grasscover on the embankment slope. Figure 3 demonstrates the use of

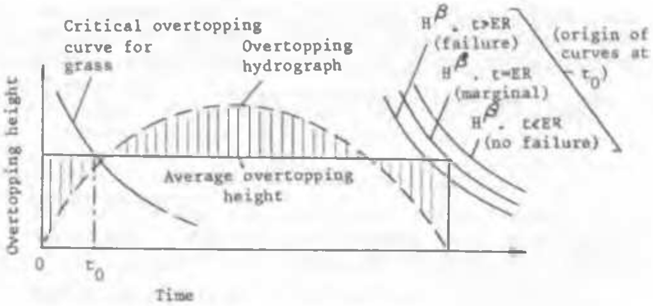


FIGURE 3: Overtopping failure evaluation including erosion resistance of the embankment.

these relationships for a given overtopping (EP) condition on a grassed embankment. The average overtopping height is deduced from the overtopping hydrograph. Failure of the grasscover has occurred when the overtopping duration exceeds the critical value predicted by the ER (grass) (critical overtopping curve for grass in figure 3). The erosion resistance of the embankment fill material comes into play after the slope protection has failed. Similar to the grasscover, the embankment will be breached when the duration of overtopping exceeds the critical duration predicted by the ER relationship for the soil (H^{β}. t › ER case). This procedure has thusfar been used in the Department of Water Affairs for the estimation of probabilities of overtopping failure.

Information on the behaviour of fill material under extreme erosive conditions is limited and practical difficulties are experienced in generating laboratory conditions similar to field conditions.

Case histories of overtopped dams (both in South Africa and abroad) revealed the following for well engineered dams:

°Gully formation is often not evident in the initial stages of erosion.

°The general "skin-erosion" pattern on the downstream side apparently applies to fill material of relatively high cohesion.

°Erosion is more irregular where the embankment consists of zones of granular fill material.

°Slope instability (of clay cores) may occur during the later stages of erosion.

The same concept of EP and ER can be applied to improved models in future even though the above-mentioned evidence may seem to suggest otherwise. The methodology will however be enhanced by the introduction of an upper limit which can be deduced from the present behaviour of dams. Since gully formation is not always evident the effect of a threefold flow concentration due to the assumed gully can therefore be ignored in obtaining an upper limit of Erosion Resistance. The hydraulic shear stress on the downstream slope of the embankment is then approximately halved, resulting in an ER-parameter twice as high as indicated above.

$$\text{Thus: } \quad ER\ (\text{extreme}) = \frac{2T.7E-8}{1E-7}$$

$$= 1.4T \qquad (3)$$

Evidence which may lead to lower Erosion Resistance is therefore ignored for the purpose of finding an upper ER limit.

A lower limit for ER would approximately be zero as is the case with a material with $Ce = \infty$.

An appropriate probability distribution should be chosen between these two limits. The point estimate method (Rosenblueth (1975)) proved to be useful in calculating the probability of failure. Point estimates (+ and -) of the ER as well as corresponding estimates of the EP values can be calculated. Taking into account the shape of the flood hydrograph, initial water level and the spillway effectiveness, the flood magnitude corresponding to these EP values is found. By means of the estimated flood frequencies a final probability of failure and confidence limits can be calculated.

Slope instability

The relatively low frequency of occurrence of this failure mode may in general not warrant a comprehensive analysis.

The Demands on the stability of the slope are gravity, pore pressure and seismic loads. Pore pressures in earth embankments vary with time and are influenced by properties of the embankment and fill material.

If piezometer (or pore pressure meter) readings are not available, these values need to be approximated from estimations of flow nets using analytical methods, electrical analogue methods or finite element models. Material properties are however needed for these analyses.

South Africa is situated in an area of low seismicity, but that does not exclude this aspect from all analyses. State-of-the-art analyses may however never be justified if seismic analyses are viewed against the record of earthquake induced dam failures. Sophisticated analyses for earthquakes in areas of relative low seismicity are therefore seldom warranted and after a subjective analysis usually included under "other" modes of failure.

The Resistance of an embankment to slope instability is determined by the strength properties of the earthfill material (cohesion and coefficient of friction), unit weight thereof and the geometric shape and composition. A bell shaped probability density function will in most cases be a reasonable approximation of these properties. The probability of occurrence of a slope failure may be approximated by using the failure domain as represented in figure 4. The failure domain is determined by several trial and error calculations of slope stabilities (of deep slides i.e. excluding surface slides) to obtain values of cohesion and coefficient of friction giving a safety factor = 1. By assuming probability density functions for both cohesion and coefficient of friction the probability of failure can be estimated as the probability of these strength parameters being in the failure domain.

This is represented by the volume under the failure domain of the bivariate distribution of cohesion and coefficient of friction. In practice numerical methods are used to calculate this probability, which is not so difficult with the help of a computer.

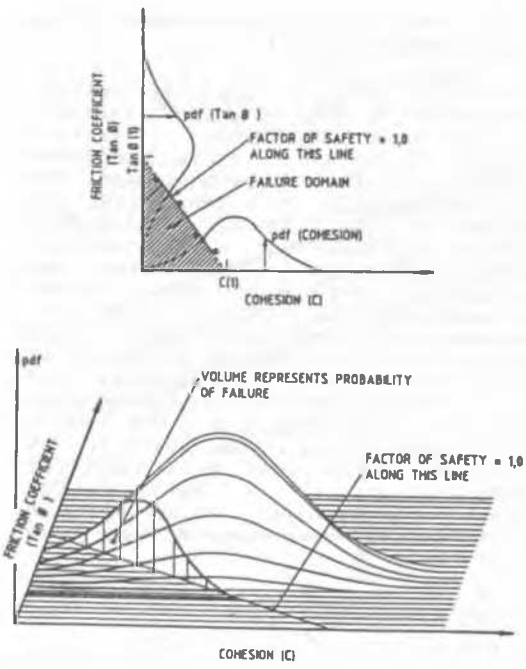


FIGURE 4: Failure domain for slope instability of earth embankments.

Improvements to the analysis could however be considered. These should make provision for the uncertain nature of the load caused by pore pressures and the variation in possible embankment conditions, including crack development, consolidation and leaching of the soil.

The variability of the possible wall condition mentioned above can be presented by various FOS = 1 lines for all the possible wall situations between a practical upper and lower limit. A probabilistic distribution can also be assigned to these possible wall conditions as indicated in figure 5.

A lower limit representing the best (most advantageous) possible wall condition anticipated in the wall based on past

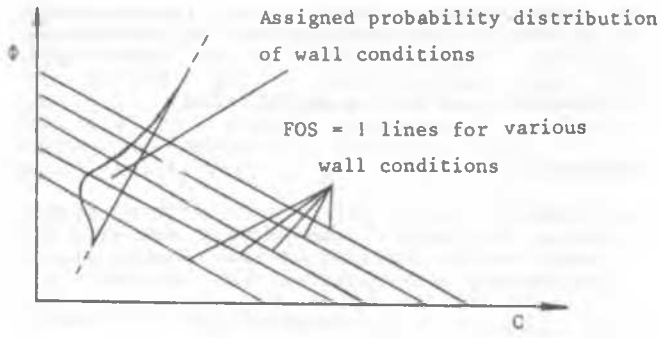


FIGURE 5: Probability distribution of the wall condition according to critical fill material strength parameters.

experience would indicate the practical lowest combination of values for cohesion and coefficient of friction. As suggested by Grivas and Asoaka (1983) a Bayesian adjustment to the cohesion and coefficient ot friction distributions (figure 6) according to the values along this lower limit line may then be sensible. The strength properties of the earthfill may however change in time owing to various factors such as consolidation (increase) and leaching (decrease) of the soil. This indicates that some adjustment over and above the Bayesian adjustment, should be made to the probability distribution of the strength properties.

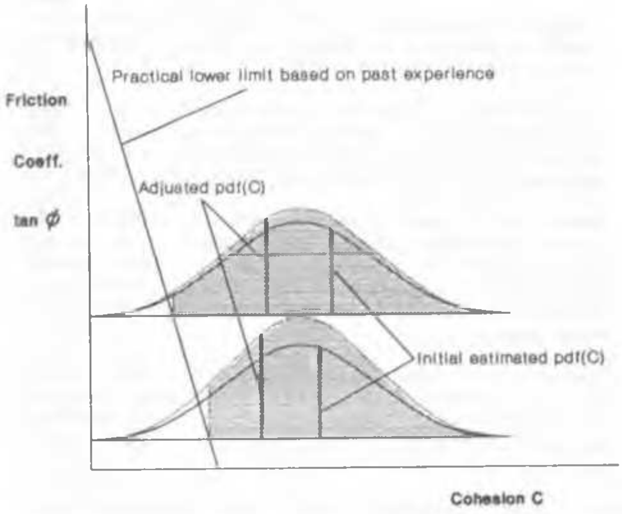


FIGURE 6: Adjustment to probability distribution of soil strength parameters due to past experience (only adjustment to cohesion probability distribution shown).

A triple integration of the cohesion, coefficient of friction and wall condition over the failure domain (figure 7) would then represent the probability of failure. Predicting a continuous probability distribution of the various wall conditions in a subjective manner would be unrealistic. A simplification would at present be sufficient. An upper and lower limit of a probable worst and best as well as expected intermediate wall condition can be predicted. From signs of the dam behaviour, a simple discrete distribution can be estimated between these limits as shown in figure 8. This simplifies the calculation to a large extent.

The spatial variation in pore pressure can be estimated by flownet analysis or piezometric monitoring from which a posterior updating of prior analyses can be done using for example the methods proposed by Hachich and Vanmarcke (1984).

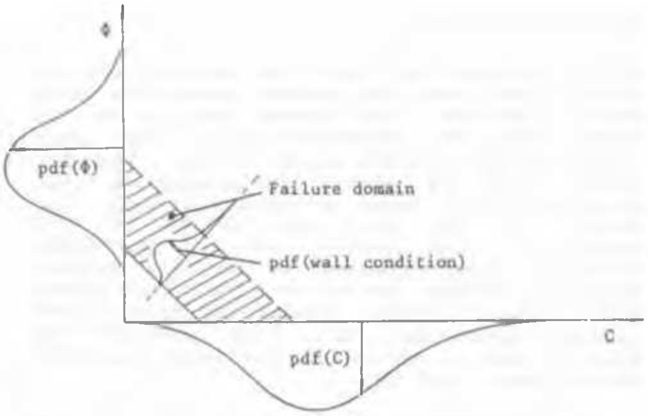


FIGURE 7: Failure domain incorporating probability distribution of wall condition.

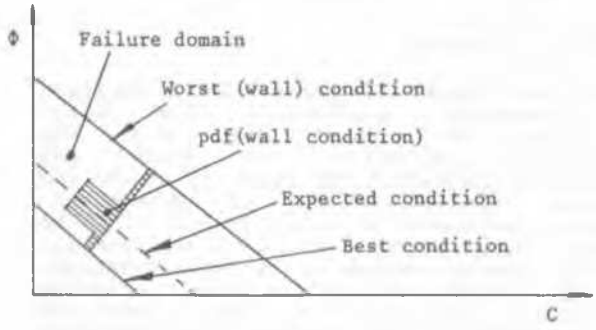


FIGURE 8: Simplified probability distribution of wall condition.

One of the prime aspects involved in the probability analysis of an embankment is the estimation of material properties. These could be estimated from past records, sampling or experience. Subjective judgement in parameter estimation is however often biased and should be applied with caution.

The combined probability distribution of the various zones of the embankment through which the slip surface passes can be estimated by means of the point estimate method. Upstream slope failure is unimportant from a safety point of view, but not from a maintenance point of view.

Other failure modes

As mentioned earlier those modes of failure which are difficult to quantify and those which play a minor role can be combined and subjectively estimated by comparison with the external erosion and slope instability modes of failure using relative probabilities. For composite dams, i.e. dams consisting of both concrete and earthfill sections, the probability of failure is usually assumed to be the lower value of the two individual sections. Owing to the fairly high frequency of piping failures, a procedure similar to the calculation of the probability of external erosion is envisaged for this mode of failure.

Evaluation of risk

Risk comprises not only the probability of failure but also the damage associated with such a failure. The damage due to a dam break can be estimated from the area inundated by the dam break flood. The dam break flood is mainly influenced by the breaching time, size of breach formed, the height of the wall and volume of the reservoir. The breach size and breaching time has been studied by amongst others MacDonald (1982), Froehlich (1987) and Singh and Scarlatos (1988). Useful dam break flood routing programmes have been compiled by Fread (1981) to establish the area inundated downstream of the dam.

The representation and evaluation of the combined probability of failure and damage may be done by means of graphs depicting the relative risk level and hazard potential as, for example, proposed by Oosthuizen (1985).

CONCLUDING REMARKS

Sufficient tools for probabilistic analyses are presently available. The major deficiency at present lies with the estimation (variation) of loads and resistance parameters by means of which the response (analysis) can be determined. Erosion resistance of soils is one of those fields which needs further exploration. Further studies leading to better estimations of the values of the material strength parameters as well as less sensitive parameters describing the material properties would enhance the methodology. More sophisticated non-destructive, remote monitoring techniques like ground penetrating radar should be explored as these could be useful in future to detect cracks and other anomalies in embankments.

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