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Factor of safety and probability of failure in concrete dams

L. Altarejos-García, I. Escuder-Bueno, A. Serrano-Lombillo & A. Morales-Torres
Universitat Politècnica de Valencia, Department of Hydraulic Engineering and Environment, Valencia, Spain

ABSTRACT: Risk analysis methodologies can be useful tools to help decision-makers in dam safety engineering. One of the inputs needed for Quantitative Risk Analysis is an estimate of the probability of failure of the dam under study. Existing dams have been designed using the factor of safety, which is a concept associated with a certain mathematical model of the physical behavior of the dam. In dam engineering practice it is usual to calculate a factor of safety for a certain failure mode to check the safety of the dam, whereas calculation of the probability of failure associated with such factor of safety is not done. Finding possible relationships between factors of safety and probabilities of failure in dam engineering may be of help for engineers performing risk analysis. In this paper, factors of safety used in several regulatory rules and guidelines of different countries for concrete dams are reviewed and the possibility of deriving relationships between them and probabilities of failure is discussed.

1 INTRODUCTION

Safety evaluation of existing and new gravity and buttress concrete dams always includes checking the stability of the dam against sliding along concrete-rock contact or along discontinuities in rock foundation, as it is shown in engineering practice in different countries. This safety evaluation is done using the factor of safety concept.

The factor of safety has been used successfully as a tool by engineers in dam design and safety review. In its more frequent form, the factor of safety is not a rigorous mathematical construct but a robust and useful tool for practical purposes. The factor of safety approach to dam safety allows safety assessment when the quality and the quantity of information is low and the degree of refinement of the safety model is low as well (Kreuzer et al., 1991). This feature is the main advantage of the factor of safety, as more refined models have to be fed with information of high quality and quantity. Assuming that this information is available, the factor of safety approach is not able to make the most of it due to its inherent limitations, so it is not an adequate tool for a refined safety assessment.

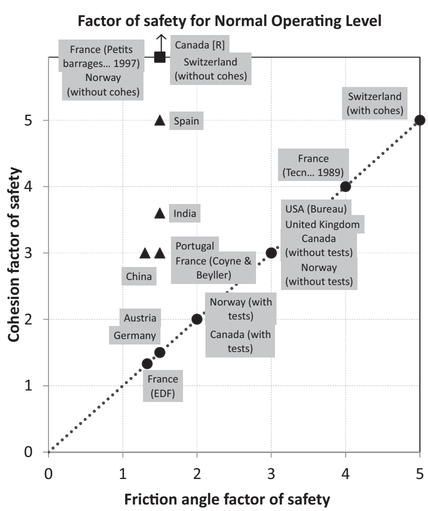
Nowadays there is a trend towards dam safety as a active and ongoing management process rather than a static deterministic statement. Tools such as risk analysis can help to give answers to some questions, and so it can help owners to make risk-informed decisions. Risk assessment tools and techniques are used routinely by several industries. Benefits from the risk analysis approach are recognized even when limited data are available. As it has been stated, risk assessment helps engineers to understand uncertainties in the project, and provides a logical process of identifying hazards, evaluating the seriousness of each hazard, and assessing the effectiveness of risk reduction measures (Silva et al., 2008).

2 FACTOR OF SAFETY IN GUIDELINES AND REGULATORY RULES FOR SLIDING FAILURE MODE

Insufficient shear strength in the foundation is the most common cause of failure of concrete dams according to ICOLD (ICOLD 1995). Regulatory rules and guidelines in most countries focus their attention on sliding of the whole dam section or part thereof along the dam-foundation contact and sliding along lift joints in the dam body or along weak planes in the foundation. The most common criterion for safety assessment against sliding is the factor of safety, defined as the ratio between the resistant forces and the driving forces along the considered sliding surface. This ratio can be defined in terms of forces or in terms of stresses. The equivalence between these two is not straightforward. In most countries three levels of loading combinations are used (usual, unusual, extreme). It is important to notice that these loadings can be defined with different criteria in different countries. Factors of safety vary with the loading (larger for usual loads).

The factor of safety has been used successfully as a tool by engineers in dam design and safety review. In its more frequent form, the factor of safety is not a rigorous mathematical construct. The shear strength is defined by a Mohr-Coulomb model, considering two strength parameters: friction angle and cohesion. In most cases, the guidelines or regulatory rules do not state if values should be peak or residual values. Some guidelines give reference values for strength parameters if no test data are available for the dam under analysis. In some cases, different factors of safety are applied to friction and cohesion strength before calculating the ratio to loading forces. In such cases, the cohesion is always affected by a large factor of safety. In some countries, safety factors also vary depending on the quality of the information of strength parameters (larger when no test are available). In Figs. 1 to 3 the different safety factors from several countries are depicted. Fig. 1 is for usual loads, Fig. 2 is for unusual loads and Fig. 3 is for extreme loads. Points along the diagonal line correspond to cases where the same reduction factor is applied to friction and cohesion.

As can be seen, the minimum factors of safety vary considerably from one country to another, and also vary for different practices of different organizations in the same country. In most cases, the information needed to carry out the analysis according to these guidelines and regulatory rules is not sufficient to do a more refined reliability-based assessment. One question arises from Figs. 1 to 3, which is how these charts should be interpreted from the dam safety point of view. ¿Do different safety factors correspond to similar probabilities of failure due to the particular characteristics of each country? ¿Are similar safety factors equivalent to different reliability assessments on the safety of the dam? According to the low level of information needed to carry out some of the analysis, even in the same country,



** The regulationsthat recommend using null cohesion are drawn in the upper part of the graph.*
[R] These factor of safety recommendations are applied in residual conditions.

Figure 1. Factors of safety in guidelines and regulatory rules for Normal Operating Level.

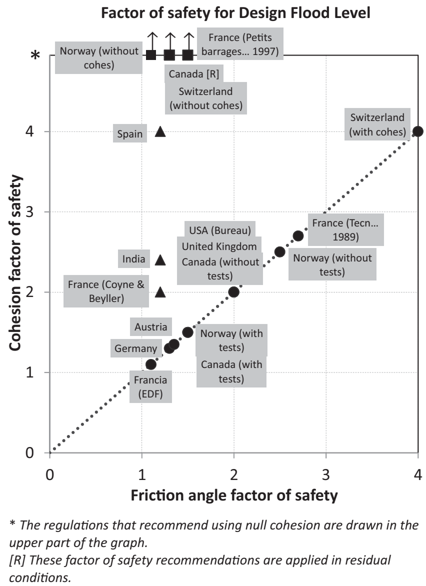


Figure 2. Factors of safety in guidelines and regulatory rules for Design Flood Level.

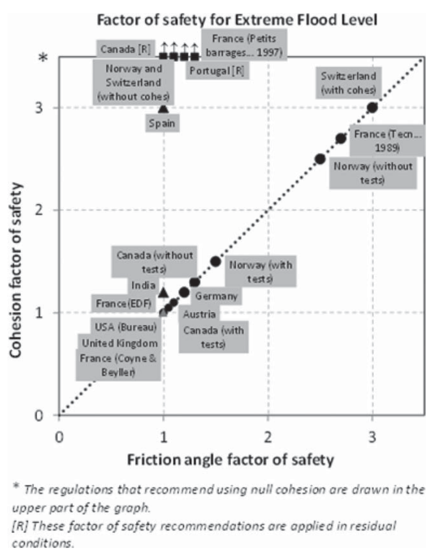


Figure 3. Factors of safety in guidelines and regulatory rules for Extreme Flood Level.

¿Do this questions make sense for different dams analysed with the same practice, guideline and/or regulatory rule?

3 FACTOR OF SAFETY, RELIABILITY, FRAGILITY AND PROBABILITY OF FAILURE

In a safety assessment, factors of safety are calculated and then they are compared with reference values to assess the safety condition of the dam, thus considering the dam as 'safe' if the calculated factor of safety is higher than the reference value or 'unsafe' if it is not. As it has been pointed out elsewhere (Smith 2003, Hoek 2007) if uncertainties are incorporated in the analysis, the factor of safety, considered as a mathematical construct, becomes another random variable, so the probability of failure is the probability P(FS < 1). According to this definition, one expects that an increase of the factor of safety will imply a decrease in the probability of failure, but it has been shown (Smith 2003, Silva 2008) that higher factors of safety do not always lead to lower probabilities of failure due to the uncertainties involved in the analysis Uncertainties in dam safety have been treated deeply by several authors (Ellingwood et al., 2001, Hartford et al., 2004, Kreuzer 2005), and include parameter and system uncertainty, but also loading uncertainty. It must be pointed out that uplift pressure is probably the most influencing factor on sliding stability (Ruggeri et al., 2004, Westberg 2009), and it is a loading effect subjected to considerable uncertainty. When there are uncertainties in the input variables reliability analysis methods can be employed to determine the probability of failure, i.e. the probability that the load effect will exceed the resistance effects. For normally distributed load and resistance parameters with means μ_L and μ_R, and standard deviations σ_L and σ_R, respectively, the reliability index is given by Equation 1.

$$\beta = \frac{\mu_R - \mu_L}{\sqrt{\sigma_R^2 + \sigma_L^2}} \tag{1}$$

The probability of the response of the dam, given some imposed load level, this is, the conditional probability of failure, can be expressed according to Equation 2.

$$\text{P(response)} = \text{P(response | loads)} \times \text{P(load events)} \tag{2}$$

This probability can be depicted graphically as shown in Fig. 4, where the conditional probability of failure is the probability P(Resistance < Loading) where the loading is represented by a single value. If this exercise is repeated mapping all feasible load values, the result is a fragility analysis. The conditional probability of failure of a gravity or buttress dam can be depicted by its fragility. A fragility analysis of concrete dams requires probabilistic models and the statistical characterization of the random variables that play a significant role in the dam's performance (Ellingwood et al., 2001). In the most common situation the necessary statistical data are limited. The difficulty and expense associated with determining the probability of failure by probability theory is one of the main reasons for the little adoption of these methodologies. When a risk analysis is conducted on a gravity dam, considering the sliding failure mode, the engineers want to estimate the probability that the dam will fail by shear along the concrete-rock contact. Fragility analysis can be of help for this purpose

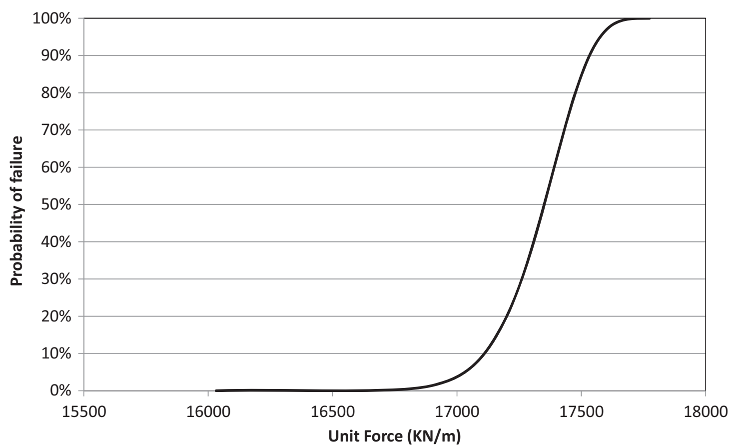


Figure 4. Definition of conditional probability of failure.

(Altarejos et al., 2009). Fragility analysis has its common graphical expression in terms of families of curves of water levels vs. (conditional) probability of failure for each failure mode considered, as in Fig. 5. As long as a fragility analysis maps the probabilities for different values along the probability density distribution of the resistance, the fragility curve obtained is the probability distribution of the resistance function.

If equivalence between factor of safety and probability of failure could be found, this is to say, if there were unique one-to-one mapping between factor of safety and probability of failure, practical engineers would be able to achieve reliability-based design by using the equivalence. Also, safety assessment of dams using risk analysis tools would benefit from this as the probability of failure could be assessed by using a factor of safety approach, which is much simpler, convenient and familiar to engineers than reliability. Relations between factor of safety and probability of failure have been explored from a rigorous and mathematical approach (Ching 2009) but also from semiempirical approaches, based on actual engineering problems and quantified expert judgement. An example of the semiempirical approach has been developed for slope failure. (Silva et al., 2008) and it include practices followed for design, investigation, testing, analyses and documentation, construction and operation and monitoring. This practical relationship between factor of safety and probability of failure has the shape plotted in Fig. 6.

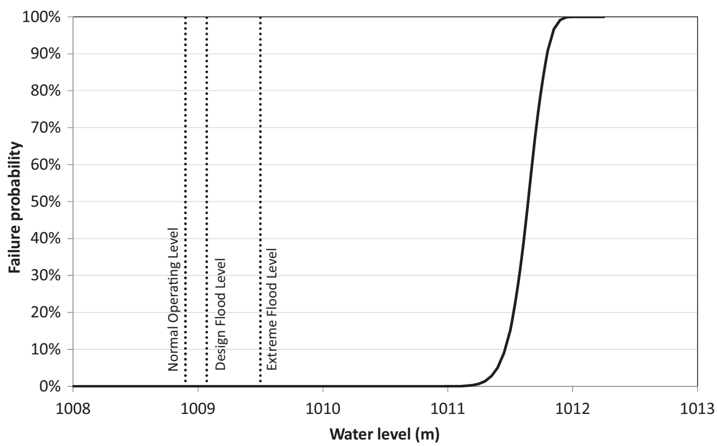


Figure 5. Fragility analysis of concrete gravity dam.

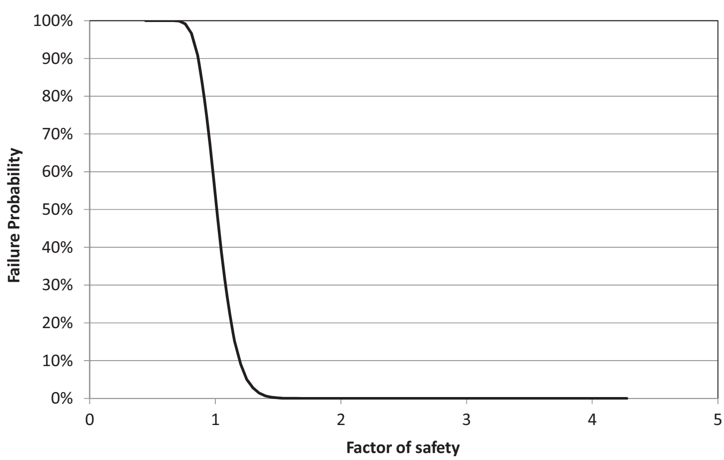


Figure 6. Factors of safety vs. probability of failure.

Either way, finding a semiempirical or a purely mathematical relationship between factor of safety and failure probability for sliding failure modes would represent a step forward for risk analysis.

4 CONCLUSIONS

Safety assessment of concrete dams against sliding is usually done with the factor of safety concept using simple Mohr-Coulomb shear strength models. Even for this simple case, strong differences are found in different countries in the minimum required factors of safety in guidelines and regulatory rules. Different safety factors are applied for different load combinations, for different levels of information on strength parameters and for different hypothesis on shear parameters (peak or residual values). This implies the recognition of several uncertainties with high influence on the safety evaluation of dams. Part of these uncertainties can be treated adequately with reliability models, provided that enough information is available. Techniques such as fragility analysis can be useful for engineers to better understand how uncertainties can affect the safety of the dam, but, on the other hand, most dam engineers are not familiar with reliability techniques. In order to reduce this gap, the search of relationships between factors of safety and probability of failure would be of great help. This relationship has been explored in general from a rigorous mathematical approach but there have been also semiempirical approaches to similar problems in the field of slope stability. It is the authors' opinion that research on this problem would benefit not only engineers involved in risk analysis problems but it will also give some insight into the meaning of the factor of safety most common engineering practice. Factors of safety found in several countries for similar loading combinations differ considerably. If solid correlations between factor of safety and probability of failure can be derived, then, a meaningful comparison in terms of probability will be possible.

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