Towards a probabilistic assessment of structural safety of gravity dams

Über eine Wahrscheinlichkeitsbewertung der strukturellen Sicherheit von Schwergewichtsmauern

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Abstract

The aim of this paper is to develop a reliability-based analysis method for structural stability of gravity dams. Methodologies are proposed for probabilistic assessment of hydraulic loads and shear strengths. Reliability Methods (FORM and Monte Carlo simulations) are used to assess cracking and shearing limit states. The procedure is illustrated on the example of a RCC gravity dam.

Zusammenfassung

Das Ziel dieses Beitrages ist es, eine zuverlässigkeitsbegründete Analysemethode für die strukturelle Sicherheit von Schwergewichtsmauern zu entwickeln Dabei werden Verfahren für die Wahrscheinlichkeitsbewertung der hydraulischen Lasten und der Scherfestigkeiten vorgeschlagen. Es werden Zuverlässigkeitsmethoden (FORM und Monte-Carlo Simulation) verwendet, um die Grenzzustände für das Aufreißen und das Abscheren zu bestimmen. Das Verfahren wird beispielhaft an einer RCC-Schwergewichtsmauer gezeigt.

1 Introduction

Dam structural safety is currently assessed in a deterministic context which is not easy to marry with a risk analysis format. Since 2006, semi-probabilistic safety assessment, inspired in Eurocodes, is beginning to be implemented in French recommendations for gravity dams [1]. The aim of this paper is to develop a reliability-based analysis method for structural stability of gravity dams. In this context, safety assessment is expressed as a limit state failure probability which could provide a more realistic risk analysis. This paper proposes methodologies for probabilistic assessment of hydraulic loads and shear strengths. The reliability analysis are finally illustrated on the example of a RCC gravity dam.

2 Loads

Seismic and hydraulic loads are often evaluated in a probabilistic context, associated to a recurrence period. This chapter focuses on hydraulics loads.

2.1 Hydraulic loads

A simple approach consists in modeling flood-level distribution by a probability law. This paper adds two mains sophistications. The first one accounts for the variability of the Headwater Level

HL at the beginning of flood events. The second one uses a model for flood frequency estimation, based on a stochastic model for generating hourly rainfall.

Initial Headwater Level (HL)

The variability of HL at the beginning of flood events is taken into account by a statistical analysis of measures coming from HL monitoring. Then, a probability law can be adjusted to the empirical distribution obtained for HL. This analysis could be made also by seasons.

This methodology is interesting in the case of dams where the HL is currently lower than the retention water level.

Flood frequency estimation by SHYPRE

The Simulated HYdrographs for flood PRobability Estimation (SHYPRE) method uses observed values to describe hydrological phenomena and successfully reproduces observed-values statistics. SHYPRE combines a stochastic model for generating hourly rainfall with a model that transforms rainfall runoff into discharge. More details of SHYPRE can be found in the reference [2].

Simulation methodology

First, the rainfall events are generated by SHYPRE for each simulated year (or season). Each rainfall event is associated with an initial HL generated by Monte Carlo simulations. Next, flood levels are evaluated taking into account the capacity of spillways. Then, a long period can be simulated by this way.

Finally, a frequency distribution can be evaluated for maximum flood level population obtained from simulations. Shape of this distribution is strongly affected by spillway configurations.

2.2 Seismic loads

In this paper, probabilistic assessment for seismic loads is made by a simple approach which consists in using a probability law for representing recurrence of a seismic coefficient used in a pseudo-static analysis.

3 Strengths

3.1 RCC

This paper concerns the body of gravity dams. Between strength parameters used in structural stability of gravity dams, the shear strength parameters are not frequently evaluated by laboratory or field tests. Then, a Probability Density Function PDF for this parameters cannot be accurately evaluated from a statistical analysis.

For a RCC gravity dam, vertical variability can be evaluated for compressive and tensile tests. Besides, vertical and horizontal variability of RCC dam can be evaluated from gamma-densimeter measures.

This chapter proposes a methodology based on an intrinsic curve formula for evaluating variability of shear parameters.

Intrinsic curve formula

Many models are available for shear strength of gravity dams: linear, bilinear, parabolic, hyperbolic and more sophisticated models. A parabolic model (**Figure 1**), Eq.(1), is used in this paper because it is defined by parameters that are regularly evaluated by means of experimental tests:

$$\tau = \left[f_C \cdot (\sigma + k \cdot f_C) \cdot \left(1 + 2 \cdot k - 2 \cdot \sqrt{k^2 + k} \right) \right]^{1/2} \cdot \left(1 - \frac{1}{6 \cdot \exp(\sigma)} \right) \qquad (1)$$

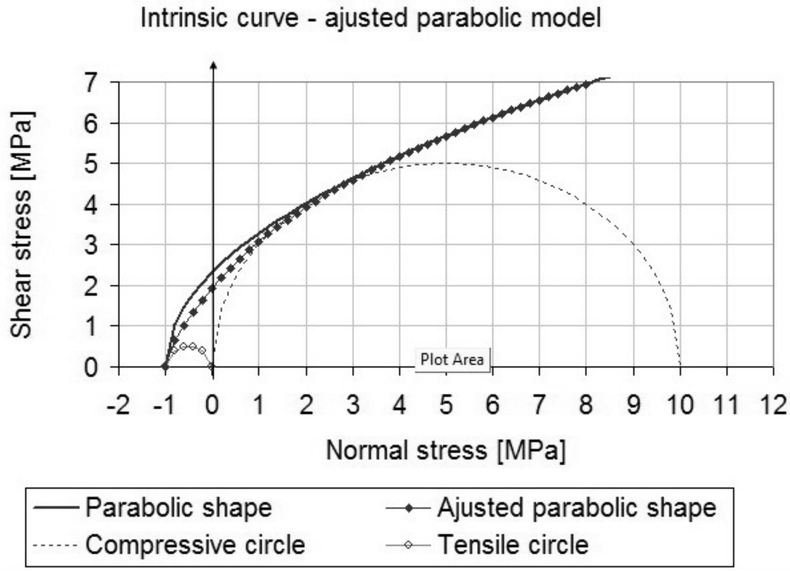

Figure 1: Intrinsic curve – adjusted parabolic shape

Where τ is the shear strength, σ is the normal stress, *fc* and *ft* are compressive and tensile strength, *k* is the quotient *ft*/*fc*. The term in parenthesis (located outside square root) is an adjustment function obtained by comparison with experimental test results presented in [2].

Cohesion, c, is evaluated from Eq.(1) with σ equal 0. Angle of internal friction, *φ*, is obtained from Eq.(1) according to normal stresses in the cross-section analyzed.

Probability Density Function PDF for shear strengths

According to data available, the proposed methodology is summarized here below:

In the case of existing dams, the first step consists in getting a population of couples *fc*, *ft* measured by experimental tests. Then, c and *φ* are evaluated for each couple *fc*, *ft* using the Eq.(1). Finally, joint PDF is obtained for c and *φ* by statistical fitting.

In the case of dams at the design stage, the experience feedback makes it possible to appreciate the order of magnitude of the variability of *fc* and *ft*. A joint PDF can then be allotted for these strengths. However, a PDF for c and *φ* cannot be obtained by an analytical way from expression proposed for the intrinsic curve. The solution that we propose is based on Monte Carlo simulations. A population of couples *fc*, *ft* can be generated by numerical simulation according to PDF selected for *fc* and *ft*.

Similarly to the case of existing dams, c and *φ* are evaluated for any couple *fc*, *ft* using the intrinsic curve formula, Eq.(1). Finally, joint PDF is obtained for c and *φ* by statistical fitting.

This methodology should not be used to predict the shear strength with high precision, but it provides an appropriate evaluation for the variability of shear strength parameters.

4 Reliability analysis

Reliability analysis are settled in a format which is compatible with risk analysis. This chapter briefly presents the probabilistic context and methods used in reliability analysis. These methods are illustrated on the example concerning the body of a RCC gravity dam.

4.1 Probabilistic context

This context may be defined in according with a random experiment E. In this study, E is related to the failure probability to cracking and shearing limit state of the gravity dam considered. E may be referred to a time period and to a critical cross-section of dam.

The considered limit state is described by a failure function (G), depending on basic random variables (x_i) and deterministic parameters which determine strengths and applied loads. If X is the vector containing basic random variables, the failure domain is defined by G(X)<0. The failure probability *Pf* can be evaluated by Eq.(2):

$$P_f = \int_{G(X)\leq 0} f(x_1,\ldots,x_n)dx_1,\ldots,dx_n \quad (2)$$

Where *f*(X) represents the joint PDF of X.

In the case of gravity dams, Eq.(2) cannot be solved analytically. First Order Reliability Method FORM and Monte Carlo Simulations MCS are used to evaluate *Pf*:

- FORM starts with a transformation of the base random variables into a normal probability space. Then, it is defined the design point (p*) as the point on the failure surface having the minimum distance (β) to the origin of this normal probability space. A linearization at the design point provides an approximate value of the failure probability:

$$Pf = \Phi(-\beta) \quad (3)$$

Where Φ( ) is the cumulative standard normal distribution.

- Retained MCS method consists in simulating outcomes for X, to introduce it in the failure function and to count the failures obtained.

4.1 Example for a RCC gravity dam

Failure function and base random variables

Failure functions is represented in this study by the following classical expression:

$$G : (c\,L + N \tan(\varphi)) - T \quad (4)$$

Where T, N are the forces acting parallel and normal to the surface under analysis; and L is the length of the contact surface evaluated by an iterative calculation according to non-cracking condition ($\sigma'_N > -ft$).

The base random variables considered are presented in (**Table 1**). The time-evolution of strengths is not taken into account in this example.

Table 1: Base random variables

Random variable	Probability law	Parameters av: average; sd: standard deviation
Compressive strength, fc	Normal, truncated at 0	av : 10 [MPa] ; sd : 1 [MPa]
Tensile strength, ft	Normal, truncated at 0	av : 0,6 [MPa] ; sd : 0,20 [MPa]
Cohesion, c	(*) Normal, truncated at 0	av : 1,3 [MPa] ; sd : 0,25 [MPa]
Coefficient of internal friction, Tan(φ)	(*) Normal	av : 1,05 ; sd : 0,07
Flood level, FL	Gumbel [4]	av : 32 [m] ; sd : 1,22 [m]
Seismic coefficient, Acc	Pareto [4]	a : 0,0097 (scale factor) p : -0,1226 (shape factor)
(*) Obtained according to methodology presented in para.3.		

Deterministic analysis

Geometrical features of the studied dam were obtained following the recommendation of the French Committee of Dams and Reservoirs. It reaches a height above ground level of 40 m, with crest and base thickness of 4 m and 26 m respectively.

Hydraulics loads are defined by a retention and maximum water level of 32 m and 38 m respectively. Seismic loads are estimated by a pseudo-static analysis, where the hydrodynamic pressures are evaluated according to Westergaard's model.

Probabilistic analysis

In this example, MCS and FORM analysis provide a Pf lower than 1E-7 for shearing limit state. Pf obtained for cracking are 6,4E-5 and 7,0E-5 by MCS and FORM analysis respectively. For shearing coupled with cracking limit states, the Pf obtained by MCS and FORM analysis are 1,0E-5 and 9,2E-6 respectively.

(**Figure 2**) shows the influence of each random variable on Pf obtained for the limit-states analyzed. It highlights the main variables requiring a special attention in risk analysis.

5 Conclusion

This paper shows the first results of a thesis inserted in the framework of quantitative risk-analysis of dams.

The paper is centered on the case of gravity dams, where it is highlighted the difficulty in evaluating the variability of parameters required in stability analysis. A methodology based on a intrinsic curve formula is proposed to evaluate the variability of shear strengths.

For hydraulic loads, flood frequency estimation is based on a stochastic model for generating hourly rainfall. The analysis considers a flood assessment according to the reservoir level at the beginning of flood events.

Reliability Methods (FORM and Monte Carlo simulations) are used in this paper to assess cracking and shearing limit states. Probability failure obtained can be used in risk analysis.

Research continues on the characterization of the spatial and temporal variability of the strength parameters in the body of dam, in the zone of contact with the foundation and inside this one.

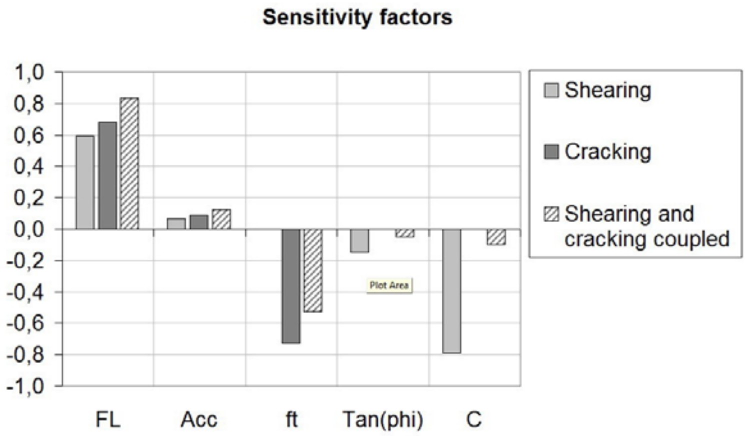

Figure 2: Sensitivity factors

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