THEME B: Probability of failure of an embankment dam due to slope instability and overtopping
Synthesis report
13th ICOLD Benchmark Workshop on Numerical Analysis of Dams

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Introduction

Dam engineers can no longer ignore the techniques of performing risk assessments, which are more and more required to sanction appropriate funds for major rehabilitations.

The analyses can range from very rigorous, complex, and costly analyses to pragmatic evaluations using semi-empirical methods, all of them dealing one way or another with typically large uncertainties to make informative decisions.

Since 2011, ICOLD Committee A is contributing to address the issue from a computational perspective, but also providing enough context to understand and pay due attention to a set of decisions that are typically made in risk analyses but also in standard design techniques (frequency of events, factors of safety, breaching parameters, etc.).

The present theme followed the tradition initiated in Valencia 2011, where the aim was analyzing the *probability of failure of a concrete dam* due to sliding failure mode, and Graz 2013, where the purpose was *comparing the estimation of consequences due to dam failure*, to focus this time on the *probability of failure of embankment dams* due to slope instability and overtopping.

In this case study, inspired by a real Spanish dam but with non-real resistance and hydrological data, the main focus consists in calculating fragility curves for slope instability and overtopping failure modes and use them to calculate annualized failure probability, accounting for both *natural* and *epistemic* uncertainty.

Problem formulation

The embankment analyzed is a homogeneous earth fill dam. Its upstream slope is 23.5 degrees and its downstream slope is 28 degrees, giving a total height of 16 meters. The normal operating level in the dam is 11 meters. This geometry is shown in Fig. 1.

In recent years, this embankment had small instability problems in the downstream slope, so a quantitative risk analysis was proposed to estimate annual failure probability. Two failure modes were analyzed in this embankment: overtopping and dam instability. In both failure modes, water pool level was supposed to be the driving force of failure.

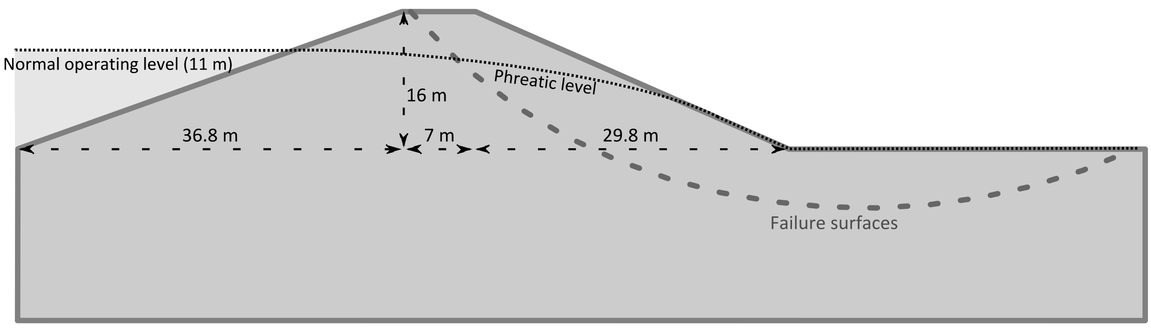

Fig. 1: Embankment Geometry.

The problem to solve was divided in five different phases:

1. **Analysis of the information for the instability failure mode:** Elaboration of a slope instability limit model for the downstream slope of the embankment and definition of the main random variables in this model. Two random variables were recommended following a Mohr-Coulomb type of failure criteria: friction angle and cohesion, although other random variables could be introduced.
2. **Calculation of reference fragility curves:** Reference fragility curve for the slope instability should be computed using the natural uncertainty distributions of the random variables defined in the previous step. Reference fragility curve for the overtopping failure mode was directly defined with a log-normal distribution. The reference fragility curves of both failure modes should be combined in order to compute a single reference fragility curve that represents the structural behavior of this embankment for different pool levels.
3. **Computation of water pool level probabilities:** The objective of this phase was calculating a relation between water pool levels and annual exceedance probability (AEP). This curve should be estimated evaluating flood routing in the reservoir for different flood events and bottom outlet availability situations, based on the floods and reservoir provided data.
4. **Computing failure probability and sensitivity analysis:** Combination of the curve computed in the previous phase with the reference fragility curve to calculate the reference failure probability. Sensitivity analysis over some of the main parameters and assumptions made in the previous phases are performed.
5. **Assessing epistemic uncertainty:** In this phase, epistemic uncertainty should be defined with a probability distribution for the mean of each random variable. These distributions were used to obtain a family of fragility curves for the instability failure mode. The family of fragility curves for the overtopping failure mode was directly defined in the formulation. Finally, the two families of fragility curves were combined to obtain a *profile of failure probability*.

Presented Contributions

Probability of Failure of an Embankment Dam Due to Slope Instability and Overtopping: First Order Second Moment Method for Assessment of Uncertainty (Andreev S.H. and Zhelyazkov A.Z.)

This solution analyzed the instability failure mode using the computer code SLOPE/W, with the limit equilibrium procedure of Morgenstern and Price and considering steady-state conditions. Properties of soil were defined of saturated and unsaturated soil. Two random variables were used: cohesion and friction angle. Monte Carlo sampling was used to calculate the conditional failure probability for instability by sampling 5000 values from the random variables for each of the prescribed pool levels, giving approximately 90% confidence in the obtained results. The obtained reference fragility curve was fitted to a Gumbel Type I distribution.

The family of fragility curves for instability was obtained modifying the reference curve following the First Order Second Moment (FOSM) method and varying the mean values of the effective friction angle and cohesion.

Next, instability and overtopping fragility curves were combined using the Uni-modal limits theorem. This curve was combined with the flood routing results to obtain a profile for the annual failure probability profile, calculated only for the case of a working bottom outlet. This profile fits precisely to a log-normal distribution with median 0.08 years^{-1}.

The sensitivity analysis of the results showed that the variation of the mean effective friction angle had the most significant effect on the median annual failure probability, followed by the use of unsaturated shear strength. Results showed large epistemic uncertainty (both from soil properties and model assumptions) for the low pool water levels.

System approach to probability of failure of an embankment dam (Westberg Wilde, M. and Vazquez Borragan, A.)

In this solution, a limit equilibrium steady-state model was created with the software Slope/W to identify slope instability. The model showed 400 failure surfaces with a critical safety factor of 1.04. Two random variables were considered in this model: cohesion and friction angle. Main epistemic uncertainties identified in this model were the assumption of saturated soils, the random variables considered, and the correlation between cohesion and friction angle.

Instability failure probability for each water level was estimated using a Monte Carlo sampling based on 2000 trials. Failure probability was estimated using the most critical failure surface in each case, although the authors point out that this approach could underestimate the failure probability, since correlation between different failure surfaces is expected to be high. Instability fragility curve was combined with the overtopping fragility curve using the two limits provided by Common Cause Adjustment techniques.

Exceedance probability for each water pool level was estimated based on the flood routing data. These results were combined with the reference fragility curve to obtain failure probability. Obtained result for failure probability is 0.055 years^{-1}.

Authors remarked that input of different slope stability parameters in the same model; such as; cohesion, friction angles, unit weight, spatial variability, point loads, seismicity, slip surface limits, cross correlation c-ϕ, and piezometric lines would have a significant impact on the results. In conclusion, they point out that with the conditions analysed the slope stability was more sensitive to epistemic uncertainties than overtopping.

Probability of Failure of an Embankment Dam Due to Slope Instability and Overtopping (Mouyeaux, A., Carvajal, C., Peyras, L., Bressolette, P., Breul, P. and Bacconnet, C.)

Two mechanical models of different complexity – one using Limit Equilibrium Method (Geostudio software) and the other Finite Element Method (code Cast3M) – were developed to assess the probability of failure due to slope instability considering cohesion and friction angle as random variables. Two hydraulic conditions (steady-state and transient) were also tested for both mechanical models.

Fragility curves were obtained using a Monte Carlo method with 1000 samples for the Limit Equilibrium models and with 10000 samples for the Finite Element model. In the second case, this estimation was made after defining the response surface with this model. Results show that the assumptions made on hydraulic conditions have a great influence on the fragility curves obtained.

Fragility curves for sliding failure mode but also overtopping failure mode were then combined using the Common Cause Adjustment. In order to compute the global failure probability of the dam, the resulting fragility curve representing the structural behavior was combined with water pool level probabilities. Results obtained show that annual failure probability for all the cases is very high (from 0.18 to 0.062 years^{-1}), although there are high differences depending on the model used to analyze instability and the hydraulic conditions (steady-state or transient) considered. The authors concluded that hypotheses used in the model strongly influence the results.

Reference solution for Theme B (Morales-Torres, A. and Escuder-Bueno, I.)

This solution was presented by the problem formulators as an example of the results expected in each phase. First, instability failure mode was analyzed with a limit equilibrium model based on the Modified Bishop method. Two random variables were considered: friction angle and cohesion. Main uncertainties detected in this model were the random variables considered and the hydraulic hypothesis made.

This model was used to estimate a reference fragility curve using 10000 samples of the random variables. Reference fragility curves of overtopping and instability were combined in a single fragility curve using Common Cause Adjustment techniques, taking the average between upper and lower limits. Exceedance probability curve for water pool levels was estimated based on a flood routing analysis. These curves were introduced in a risk model made with iPresas software in order to estimate annual failure probability, obtaining a result of 0.004 years^{-1}. Results show a significant influence of the number of Monte Carlo simulations made.

Finally, a family of fragility curves for the instability failure mode was obtained repeating the previous process but modifying the distributions of the random variables as indicated in the problem formulation. The family of fragility curves for instability and overtopping failure modes were introduced in the risk model to obtain a failure probability profile.

Comparison of results

Firstly, as can be observed in the previous descriptions, very different instability approaches were considered by participants, from simple limit equilibrium models to complete finite element models. In addition, two different assumptions were compared for hydraulic conditions: steady-state or transient.

When the fragility curves obtained with these models are compared (Fig. 2), it can be observed that the participants obtained very different results, although all of them used the same random variables with the same distributions and the same geometry. These results show the high influence of the hypothesis made and the model considered in the

instability results. Results show also a significant influence of the number of Monte Carlo simulations made. In the Benchmark discussion, it was highlighted that the hydraulic hypothesis are especially significant. In this case, considering a steady-state could lead to underestimate the slope resistance capacity.
In any case, it should be remarked that when numerical models are set up, many small hypothesis are made that can influence the results. For instance, in this problem two participants with the same software, the same geometry and the same random variables obtained very different fragility curves.

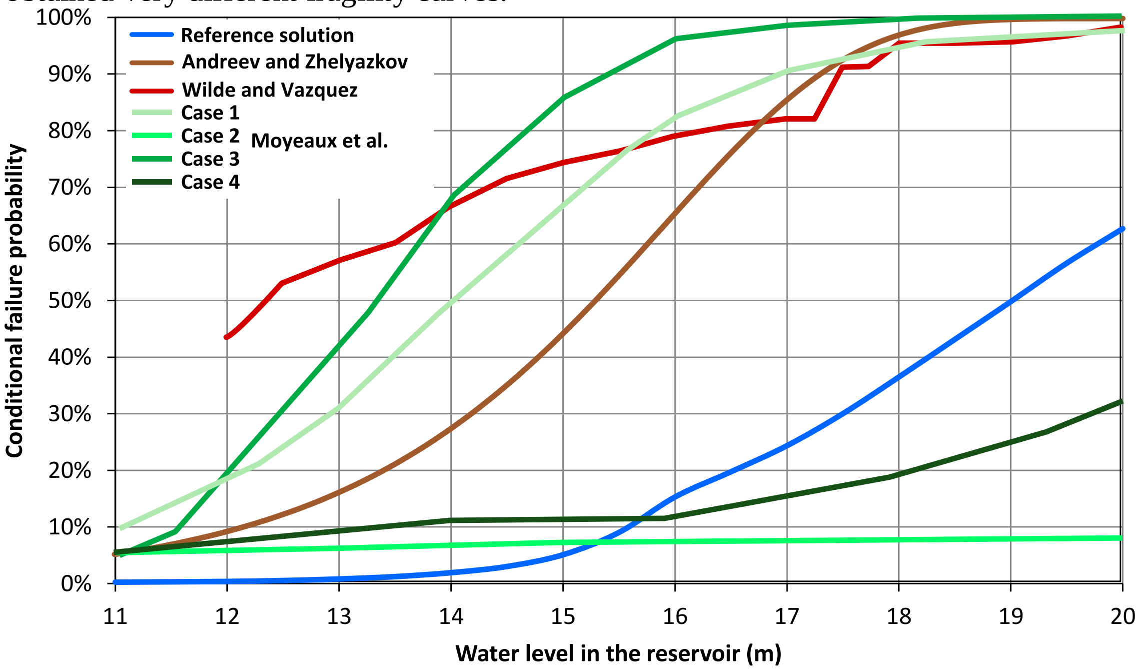

Fig. 2: Comparison of fragility curves computed by Theme B participants.

Secondly, all the participants concluded that the slope instability was clearly more significant than overtopping according to the results. In the four solutions, Common Cause Adjustment techniques were used to combine both failure modes. Using the upper or lower limit for this combination did not have a high influence on the results, since the slope instability failure mode is clearly predominant and overtopping is only activated for water pool levels with very low probability.
Thirdly, all the participants obtained very similar exceedance probability curves for water pool levels. All of them use the same floods and reservoir data and flood routing rules were very simple, so flood routing results are very similar in the four solutions.
Fourthly, the comparison of the results obtained for the annual failure probability show high differences, differing more than one order of magnitude. These differences are mainly due to the different fragility curves for instability used to compute it, which shows that the hypothesis made in the numerical models to analyze this failure mode are clearly conditioning the results.
In all the solutions, high values of annual failure probability were obtained. These high results are due to the modification of the dam resistance and hydrological data made by the problem formulators in order to increment conditional failure probabilities, reducing the number of samples and computations needed to characterize them.
Finally, only two contributions estimated the families of fragility curves and the failure probability profile to assess epistemic uncertainty, as shown in Fig. 3. There are high

differences in these two profiles, in line with the differences of the fragility curves obtained with the instability models.

In both solutions, failure probability profiles showed that small variations in the resistance parameters distributions produce important variations in the obtained fragility curves. This result remarks the importance of assessing epistemic uncertainty separately.

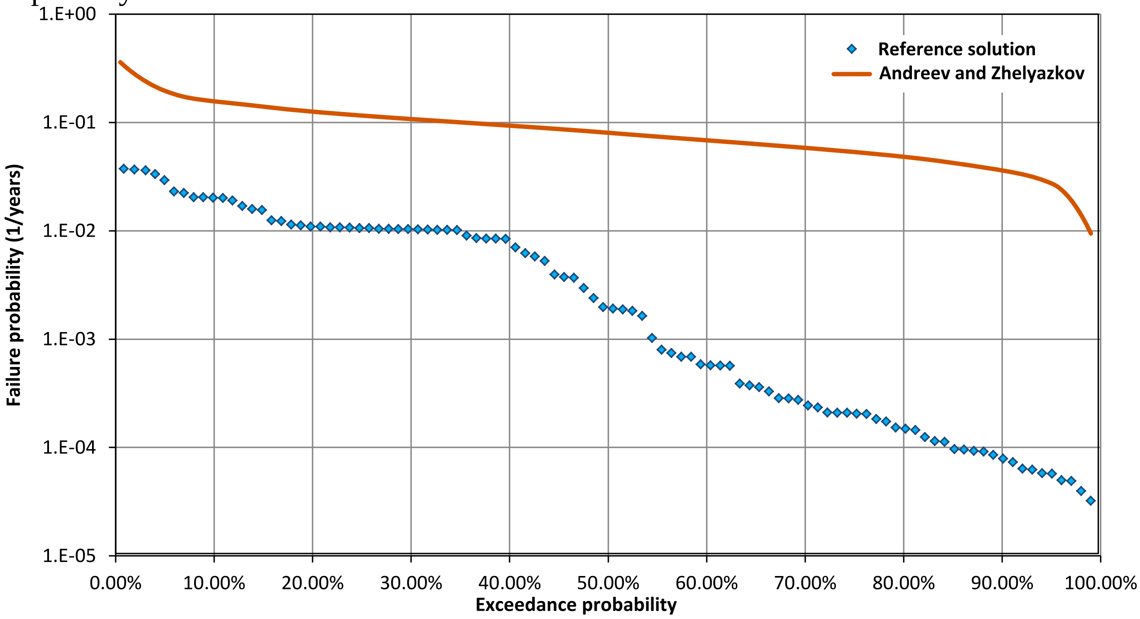

Fig. 3: Comparison of failure probability profiles computed by Theme B participants.

Conclusions

The main differences between the contributions results are due to the differences in the fragility curves introduced in the instability failure mode. The comparison made showed that very different results can be obtained depending on the hypothesis made in the models, even using the same geometry and resistance parameters. Hydraulic conditions hypothesis had an especially high influence in the results. Therefore, uncertainty is not only produced by the resistance parameters, other uncertainty sources are the slope instability model used and the hydraulic behavior of the embankment.

In this sense, risk analysis has demonstrated to be a useful tool to analyze the impact of the hypotheses made on the results. In addition, the obtained results can indicate where uncertainty reduction efforts should be focused. For this reason, in practice the distinction between natural and epistemic uncertainties is fundamental in geotechnical and dam safety governance.

Finally, the Problems Formulators would like to acknowledge and thank the Theme B participants for the very different and interesting solutions that they obtained. These solutions allowed enriching and stimulating discussions during the Benchmark.