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Computational Aspects of Dam Risk Analysis: Findings and Challenges

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ABSTRACT

In recent years, risk analysis techniques have proved to be a useful tool to inform dam safety management. This paper summarizes the outcomes of three themes related to dam risk analysis discussed in the Benchmark Workshops organized by the International Commission on Large Dams Technical Committee on "Computational Aspects of Analysis and Design of Dams." In the 2011 Benchmark Workshop, estimation of the probability of failure of a gravity dam for the sliding failure mode was discussed. Next, in 2013, the discussion focused on the computational challenges of the estimation of consequences in dam risk analysis. Finally, in 2015, the probability of sliding and overtopping in an embankment was analyzed. These Benchmark Workshops have allowed a complete review of numerical aspects for dam risk analysis, showing that risk analysis methods are a very useful tool to analyze the risk of dam systems, including downstream consequence assessments and the uncertainty of structural models.

1. Introduction

A reliable evaluation of safety levels for structures such as dams—which have a very strong socioeconomic impact on local areas, and which can represent a potential hazard for the people and environment that may be affected by their presence—is of the utmost importance for the different stakeholders involved.

The capability of numerical models to contribute in engineering practice to the quantitative evaluation of the safety margins of structures is nowadays taken for granted in the dam engineering domain, thanks in part to the great amount of work done by the International Commission on Large Dams (ICOLD) Technical Committee on "Computational Aspects of Analysis and Design of Dams." However, the application of numerical models to real-world problems has suffered for some time from the gap between mathematical modeling specialists and dam engineers and managers. The first group includes information system specialists who are able to develop computer models to their full potential, while the second group often comprises professionals who prefer to revert to traditional methods of calculation and empirical methods based on their proven experience. The main aim of the Committee was to contribute to the filling of this gap and to promote the diffusion of computer software in the field of dam engineering. The Committee was appointed by ICOLD as an *ad hoc* committee in 1988; finally, during the 2005 ICOLD Annual Meeting, the Committee was appointed as a permanent Technical Committee.

In its intent to guide and help dam engineers wishing to make correct use of computer programs and numerical models, the Committee has promoted a wide-ranging benchmarking program. So far, 13 Benchmark Workshops have been organized; the first occurred in 1991 (in Bergamo, Italy), and the most recent one took place in 2015 (in Lausanne, Switzerland). Among the different technical aims of the Committee activities, the following aims are worth mentioning: the creation of a stronger link between observed dam behavior and the modeling process; the issuing of guidelines to be used for educational purposes in current practice; the promotion of mathematical modeling improvements to approach safety-related problems; and the assessment of the potentialities of computer codes in order to optimize design,

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instrumentation, surveillance, and safety/risk evaluation procedures. Regarding the last topic, three themes tightly connected to risk assessment have been proposed from 2011 to 2015 (Fig. 1), for which the main different phases of the process have been extensively investigated. The present paper describes in detail those themes proposed in the Benchmark Workshops in 2011, 2013, and 2015 related to dam risk assessment and the main results obtained.

2. Valencia 2011: Estimation of the probability of failure of a gravity dam for the sliding failure mode

The 11th ICOLD Benchmark Workshop on Numerical Analysis of Dams took place in Valencia from October 20 to 21, 2011. The objective of Theme C of the 2011 edition was to obtain relationships between water pool levels, factors of safety, and probabilities of failure for an 80 m high gravity dam considering the sliding failure mode (foundation contact). Different models were used for the analysis of the dam and its foundation, along with reliability techniques. Contributions from eight teams were reported; these can be found in Ref. [1]. The 8 participant teams were from Ricerca Sistema Energetico (RSE), Technical University of Bucharest (UTBC), Sogreah Consultants (SC-AG), JSC "Vedeneev Vniig" (VNIIG), Polytechnic University of Valencia (UPV), Royal Institute of Technology of Sweden (RIT), Polytechnic University of Madrid (UPM), and Ingeniería de Presas (iPresas). The following process was followed to solve the formulated problem.

2.1. Factor of safety

First, each group of participants chose a 2D model to compute the factor of safety (sliding failure mode) for different water pool levels. All contributors considered at least a 2D rigid-body limit equilibrium model (LEM). Despite the strong evolutions developed in more sophisticated, finite element-based models, LEM is still recognized by contributors as the most popular and accepted method to evaluate dam safety for this failure mode [2]. In LEMs, the evolution of the horizontal crack was simulated as reducing the effective area at the contact interface between the dam and its foundation that provides resistance to the overturning moment. Two teams also considered deformable-body models to evaluate the crack length, implemented in finite element model (FEM) codes. In these models, different approaches were used to simulate the horizontal crack. Factor of safety was computed for two cases: effective and ineffective drains. Fig. 2 shows differences among team results for the first case.

As can be observed in Fig. 2, there are significant differences among the results prior to the application of reliability techniques. These differences are mainly due to the selected hypothesis and setup. Another important aspect is how the factor of safety was defined. As shown in Fig. 2, using the same LEM of analysis and data set of strength parameters does not necessarily result in the same outcomes.

2.2. Friction angle and cohesion

Next, each group defined the distribution of selected random variables: friction angle (ϕ) and cohesion (c). The decision regarding how friction was considered (i.e., whether the random variable is the friction angle, ϕ, or the friction coefficient, $\tan\phi$) had some impact on the results obtained. Based on results, it seems that when $\tan\phi$ is selected and a normal probability density function (PDF) is assumed, probabilities are higher than when an analysis uses ϕ as the selected parameter and considers it to be normally distributed.

Another decision is what PDF may be reasonable to use. In this case, an unusually high number of data were provided to make the process easier; however, this is not always the case in real-world problems, where few data are available (if any). Despite the data provided, several distributions were suggested or considered by contributors (normal, log-normal, Rayleigh, and beta distributions).

Decisions related to PDFs are not only linked to the selected distributions but also to the physical meaning of the given adaptation. When an unbounded PDF is used as the normal distribution, the required decision on its truncation becomes a key point of the analysis process, as shown in the results. Again, engineering judgement comes into play when assessing the minimum values to be adopted for the truncation of a PDF.

2.3. Failure probability

Next, participants estimated the probability of failure for the sliding failure mode using at least a Level 2 reliability method and a Level 3 Monte Carlo simulation method. These reliability methods are described in detail in Ref. [3]. The type of reliability method used also had a significant impact on results. Analysis with Level 2 methods is relatively easy to perform and, as long as the number of variables is low, is not time-consuming. Level 3 Monte Carlo simulation methods provide more precise results, but the computing effort may be much higher. Level 2 and Level 3 methods were used in combination with the LEM of analysis. In general, Level 3 reliability methods provided lower failure probabilities than Level 2 methods.

2.4. Event tree modelling

Finally, many teams combined the results of the two proposed drainage system conditions, and the total failure probability was obtained by combining individual probabilities in an event tree. Results for Level 3 methods are shown in Fig. 3, including analyses made by teams from RSE, RIT, VNIIG, UPV, UPM, and iPresas.

Fig. 3 shows significant differences in the results that were obtained by the participants. Most of these differences are due

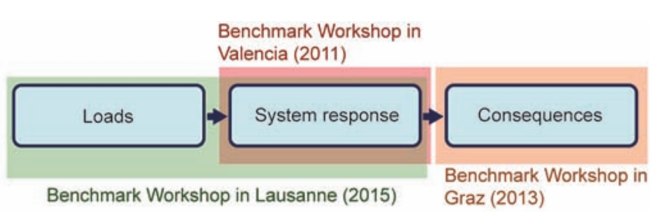

Fig. 1. Connection among themes and risk components of Benchmark Workshops.

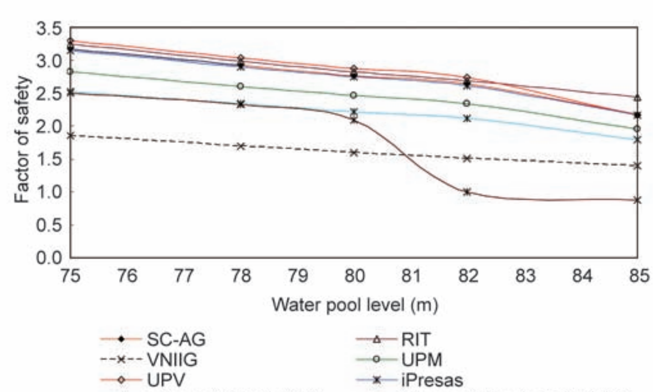

Fig. 2. Relation between factor of safety and water pool level obtained by participants for the "drains effective" case.