TECHNICAL SESSION - 1

UNCERTAINTIES AND RISK MANAGEMENT IN DAMS

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DECISION MAKING UNDER UNCERTAINTY ON RISK-INFORMED DAM SAFETY MANAGEMENT: WHICH ACTION GOES FIRST?

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ABSTRACT

Dams and water reservoirs play a key role providing a range of economic, environmental, and social benefits, including hydroelectric power, irrigation, water supply, flood control, and recreation worldwide. However, their potential failure might produce important economic and social impacts in downstream areas. Therefore, it is of high importance to characterize, analyse and evaluate existing risks and the factors that influence the potential failure of dams (dam aging, deterioration, changes on socio-economic developments, climate change, etc.). A holistic approach is necessary to meet current and future challenges on dam safety governance, supported by comprehensive and quantitative risk analyses.

In recent years, different successful cases on the application of quantitative risk analysis to inform dam safety governance can be found and these techniques are now applied worldwide. Examples can be found in United States, Spain, Australia or India.

This paper is focused on how quantitative risk results can be useful to inform dam safety management, but also on the importance of analysing uncertainty to provide robust and comprehensive information for decision-making.

Quantitative risk results can be used to prioritize investments for risk reduction based on the consideration of risk indicators that help to define the optimal sequence of risk reduction measures.
An example of independent analysis of natural and epistemic uncertainty in quantitative risk models for dams is presented, along with the analysis of how epistemic uncertainty may prioritization of investments based on risk outcomes through the use of specific metrics.

Conducting uncertainty analyses may support decisions on how to allocate resources for reducing uncertainty, for example through further investigation, tests or surveys.

1. INTRODUCTION

1.1. Risk-Informed Dam Safety Management

The aim of analysing and evaluating risk of a dam-reservoir system is to support decision-making on safety management. Outcomes from a qualitative or quantitative risk analysis, and the comparison of existent risk with other scenarios that capture the impact of planned or proposed risk reduction measures, may help authorities, dam owners, operators and other actors on how to develop improved dam safety and emergency actions.

As can be found in the literature (SPANCOLD, 2012; Morales-Torres et al., 2016) and shown by recent examples of application, prioritization of risk reduction measures based on equity and efficiency principles is required to allocate investments and establish risk reduction programmes. For example, the Technical Guide “Risk Analysis Applied to Dam Safety Management” published by SPANCOLD in 2012 describes the process for conducting a dam risk analysis and how to establish the sequence of risk reduction actions. This process has been already applied not only in Spain but also in other countries (e.g. Albania, Sweden, Uruguay or Argentina) and it is now being applied for a pilot case study in India under the framework of the DAMSAFE project (www.damsafe.eu).

Different risk indicators can be found to analyse and justify prioritization of risk reduction measures, e.g. the “adjusted cost per statistical life saved” ACSLS indicator (Bowles, 2004). These indicators consider either efficiency and/or equity principles. The analysis of different indicators for a set of risk reduction measures may support decision-making on flood risk management. In addition, there exist software tools to analyse and compare risk results based on some of the aforementioned indicators (SPANCOLD, 2012).

The use of risk indicators for defining the optimal sequence of risk reduction measures for a system is a powerful tool for supporting decision-making (Morales-Torres et al., 2016). However, it should be complemented by uncertainty analyses to evaluate the impact of uncertainty on such decisions.

1.2. The need for conducting sensitivity and uncertainty analysis

Sensitivity and uncertainty analyses may improve our knowledge of the dam-reservoir system and the factors that influence risk and reduce epistemic uncertainty. Results from sensitivity and uncertainty analyses may be compared with outcomes from analysing existing risk for a dam-reservoir system (often called as Base Case) and to evaluate confidence of obtained risk estimates and identify the need for further work on gathering new information or data. Consequently, decisions can be supported by outcomes from risk analysis from a comprehensive perspective, taking into account the impact of key risk factors on conclusions derived from the analysis.

When conducting a quantitative risk analysis for a dam-reservoir system, input data is obtained mainly from existing studies (e.g. hydrologic or hydraulic models) and additional estimations on system characteristics. Sensitivity and uncertainty analyses will help to allocate efforts to carry out more detailed analyses of specific variables (e.g. flood hydraulic characteristics, life-loss estimations, dam monitoring and surveillance, etc.). It should be recognized that there exist a certain level of uncertainty when analysing a system, but epistemic uncertainty can be reduced and should be taking into account for making decisions on how to prioritize actions for risk reduction. For such purpose, this paper presents a case example on how uncertainty analyses may help to support decision for risk-informed dam safety management.

2. UNCERTAINTY IN DAM RISK ANALYSIS

2.1 Natural and epistemic uncertainty

In general, two types of uncertainty are considered: natural and epistemic uncertainty (SPANCOLD, 2012):

- Natural uncertainty is produced by the inherent variability in natural processes and it includes temporal variability or the variability across the space of a given phenomenon (e.g. variability on rainfall intensity or on dam foundation properties). This type of uncertainty cannot be reduced, though it can be estimated.
- Epistemic uncertainty refers to the lack of knowledge or information about the system. However, it is very difficult to estimate or quantify this uncertainty. Allocating resources adequately, epistemic uncertainty can be reduced.

2.2. Dealing with epistemic uncertainty in quantitative risk models

In the dam safety field, both types of uncertainty are generally introduced in risk model inputs, without specifically distinguishing the effect of epistemic uncertainty and generally giving more importance to natural uncertainty. These results are very useful to prioritize risk reduction investments, but the following questions should be answered: How is epistemic uncertainty influencing the decisions made based on risk results?

This paper presents a case example on the use of two numerical indicators named *Indices of Coincidence* that measure the effect of epistemic uncertainties in risk-informed decision making. These indices are computed comparing the effect of epistemic uncertainty in prioritization sequences of potential risk reduction measures. These sequences of measures are obtained based on the procedure proposed by Morales-Torres et al. (2016). Hence, two different indices are considered in this paper to measure the effect of epistemic uncertainty in the calculation of prioritization sequences. The two indices are:

- Index of Coincidence (IC): It quantifies the difference in the order of measures between two sequences. For each step, it is computed with the division of the difference in the position of a sequence in the two itineraries and the maximum difference in the position that there could be.
- Adjusted Index of Coincidence (AIC): It is computed multiplying the Index of Coincidence in each step by a factor to preponderate the first measures of the sequence, since they are more important in the decision making process.

Thus, these indices of coincidence can be used to compare each implementation sequence obtained through a second-order probabilistic risk analysis with the reference implementation sequence obtained with a first-order probabilistic risk analysis. Consequently, a high number of Indices of Coincidence is obtained, one for each sequence. The average Index of Coincidence is an indicator on how epistemic uncertainty is influencing decision making, since it indicates the differences in the order of measures that epistemic uncertainty could produce. Table 1 shows reference values proposed by the authors of average Indices of Coincidence and what they could indicate when computed for a single source of uncertainty.

Table 1: Indicative meaning of average Index of Coincidence.

Average Index of Coincidence value	Degree of influence
> 99%	Low
95% - 99%	Low-Medium
95% - 85%	Medium
85% - 75%	Medium-High
75% - 60%	High
< 60%	Efforts should be focused on reducing epistemic uncertainty before significant investments in risk reduction

3. CASE EXAMPLE

In this section, the aforementioned approach is applied to inform safety management in four existing concrete gravity dams in Spain. The starting point for the analysis is the result from quantitative risk models elaborated within a first-order probabilistic risk analysis performed on each dam. The analysis made is focused on the potential sliding failure mode and the epistemic uncertainty about foundation resistant capacity. Hence, the analysis is focused on this source of epistemic uncertainty and how it can influence decision making.

A total number of 20 potential risk reduction measures have been analyzed. These structural and non-structural measures came from a list of actions already planned by the operators, including new operating rules, emergency procedures, outlet works, and dam foundations.

The procedure described in (Morales-Torres, 2017) has been followed to obtain a family of fragility curves. Two independent random variables are considered within a Limit Equilibrium Model: friction angle and cohesion. A family of 1000 fragility curves was obtained for each dam (the example for dam A is shown in Figure 1). The spread of this family is an indicator of the influence of the epistemic uncertainty.

Second, the family of fragility curves was incorporated in the quantitative risk model in order to obtain a risk probability distribution for sliding failure. These risk models have been elaborated using iPresas Calc software (iPresas 2014), which is based on event trees to compute failure probability and risk. For each dam and fragility curve, risk models are used to compute the dam failure probability, economic and societal risks.

Third, Indices of Coincidence have been computed to analyse the influence of epistemic uncertainty on decisions. With this purpose, the 20 risk reduction measures have been prioritized using the EWACSLS indicator (Serrano-Lombillo et al. 2016), combining equity and efficiency principles.

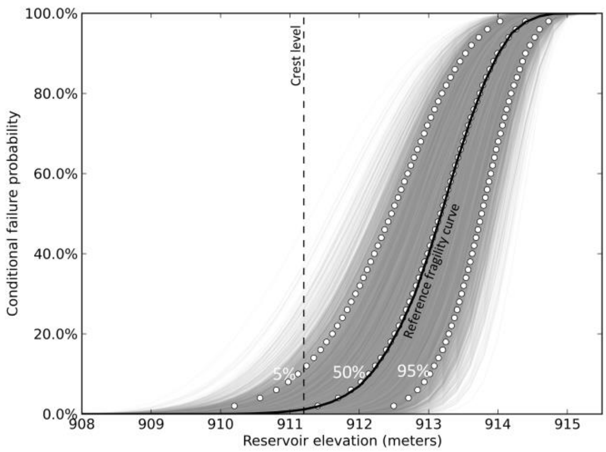

Figure 1: Family of fragility curves obtained for Dam A.

Consequently, a reference implementation sequence of measures is obtained from the reference fragility curve in each dam. Next, 1000 implementation sequences were calculated combining the 1000 fragility curves for each dam. These 1000 sequences are compared with the reference sequence to obtain the average Indices of Coincidence shown in Table 2 (Base Case). As can be observed in Table 2, Indices of Coincidence are lower for Dam B, which indicates that epistemic uncertainty has a higher influence on decision making, so uncertainty reduction actions are more recommended. In contrast, Indices of Coincidence for Dam A are close to 100%, which indicated that epistemic uncertainty has low influence on decision making. Indices of Coincidence of Dams C and D indicate a medium influence of epistemic uncertainty on results. Finally, the potential effect of epistemic uncertainty reduction measures for the foundation resistance capacity, like geotechnical tests and detailed surveys, has been analyzed. With this purpose, the previous computations have been repeated but reducing by half the standard deviation of the epistemic uncertainty probabilistic. Thus, Indices of Coincidence have been recomputed for these cases as shown in Table 2.

Table 2: Indices of Coincidence: base case and after reducing epistemic uncertainty.

	Base case		**Epistemic uncertainty reduction**		**Difference**	
	IC	**AIC**	**IC**	**AIC**	**IC**	**AIC**
Individual analysis						
Only in Dam A	99.35%	99.29%	99.94%	99.94%	0.60%	0.66%
Only in Dam B	79.86%	69.55%	83.19%	74.55%	3.34%	5.00%
Only in Dam C	87.42%	86.97%	89.38%	89.57%	1.96%	2.60%
Only in Dam D	94.11%	90.77%	96.74%	94.55%	2.63%	3.78%
Combined analysis						
Only in Dam A	86.95%	86.60%	87.76%	87.16%	0.80%	0.56%
Only in Dam B	86.95%	86.60%	87.23%	87.02%	0.27%	0.42%
Only in Dam C	86.95%	86.60%	88.35%	87.74%	1.40%	1.14%
Only in Dam D	86.95%	86.60%	88.22%	88.11%	1.26%	1.51%
All dams	86.95%	86.60%	91.28%	90.68%	4.33%	4.08%

Results show that reducing epistemic uncertainty in Dams C and D would have a higher influence in the decision making process for the whole system. Epistemic uncertainty reduction in Dam B has a high effect in the sequences obtained individually but its effect at system scale is more limited.

4. CONCLUSIONS

Dam-reservoir systems are located in natural and heterogeneous environment that cannot be fully characterized. Therefore, dam safety governance deals with higher natural and epistemic uncertainties than other sectors. For this reason, there is a need to analyse the impact of epistemic uncertainty on decision making.

This paper provides an example on the use of new metrics to analyze the influence of epistemic uncertainty. The process is based on the results of a second-order probabilistic risk analysis, which requires separating natural and epistemic uncertainty within risk model input data. These metrics are computed by combining results of a second-order probabilistic risk analysis and prioritization of investments based on risk reduction indicators.

The presented case study is focused on one source of uncertainty within the risk model related to foundation resistant capacity. This approach provides a better understanding of what type of epistemic reduction actions are more effective. Although the case study deals with epistemic uncertainties related to system response, this approach can also be used to analyze the effect of epistemic uncertainty in risk terms: loads and consequences.

In conclusion, this type of metrics have significant advantages to inform dam safety governance, since they allow measuring the effect of epistemic uncertainty in decision making and they may help to identify needs for reducing gaps in dam knowledge.

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