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EVALUATION OF THE IMPACT OF RISK REDUCTION INDICATORS AND EPISTEMIC UNCERTAINTY IN DAM SAFETY GOVERNANCE

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ABSTRACT

Large dams are critical infrastructures whose failure could produce high economic and social consequences. For this reason, in recent years, the application of quantitative risk analysis to inform dam safety governance has risen significantly worldwide.

This thesis is focused in how computed quantitative risk results can be useful to inform dam safety management. It proposes different methods and metrics to deal with the two key issues identified in this process: how risk results can be managed to prioritize potential investments and how uncertainty should be considered in quantitative risk models to inform decision making.

Firstly, it is demonstrated that risk reduction indicators are a useful tool to obtain prioritization sequences of potential safety investments, especially in portfolios with a high number of dams. Different indicators for dam safety are assessed, analyzing their relation with equity and efficiency principles.

Secondly, it is proposed to consider explicitly and independently natural and epistemic uncertainty in quantitative risk models for dams, following the recommendations developed by other industries. Specifically, a procedure is developed to separate both types of uncertainty in the fragility analysis for the sliding failure mode of gravity dams.

Finally, both issues are combined to propose different metrics that analyze the effect of epistemic uncertainty in the prioritization of investments based on risk results. These metrics allow considering the convenience of conducting additional uncertainty reduction actions, like site tests, surveys or more detailed analysis.

RESUMEN

Las grandes presas son infraestructuras críticas cuyo fallo puede producir importantes consecuencias económicas y sociales. Por este motivo, en los últimos años la aplicación de técnicas de análisis de riesgos para informar a la gobernanza de la seguridad de presas se ha extendido por todo el mundo.

La presente tesis se centra en analizar cómo los resultados calculados de riesgo pueden ser útiles para la toma de decisiones en seguridad de presas. Para ello, se proponen diferentes métodos e indicadores que tratan los dos principales problemas identificados en este proceso: cómo gestionar los resultados de riesgo para priorizar potenciales inversiones en seguridad y cómo debe ser considerada la incertidumbre en los modelos de riesgo para orientar a la toma de decisiones.

En primer lugar, se muestra como los indicadores de reducción de riesgo son una herramienta útil y eficaz para obtener secuencias de priorización de potenciales medidas de reducción de riesgo, especialmente en la gestión conjunta de grandes grupos de presas. Por ello, los diferentes indicadores para la gestión de la seguridad de presas son evaluados, analizando su relación con los principios de eficiencia y equidad.

En segundo lugar, se propone considerar la incertidumbre epistémica y la incertidumbre natural de forma independiente dentro de los modelos de riesgo cuantitativos para presas, siguiendo las recomendaciones de otras industrias. En particular, se propone un procedimiento para separar ambos tipos de incertidumbre en el análisis del modo de fallo por deslizamiento en presas de gravedad.

Finalmente, ambos puntos se combinan para proponer diferentes índices que analicen la influencia de la incertidumbre epistémica sobre las secuencias de priorización obtenidas mediante indicadores de reducción de riesgo, y por lo tanto, sobre la toma de decisiones. De esta forma, estos índices permiten analizar la necesidad de realizar acciones adicionales para reducir la incertidumbre epistémica, como ensayos, sondeos o estudios detallados.

RESUM

Les grans preses son infraestructures crítiques que si fallen poden produir importants conseqüències econòmiques i socials. Per aquest motiu, en el últims anys la aplicació de tècniques d'anàlisis de rics per a informar a la governança de seguretat de preses s'ha estès per tot el món.

Aquesta tesi es centra en analitzar com els resultats calculats de risc poden ser útils per a prendre decisions en seguretat de preses. Per a això, es proposen diferents mètodes i indicadors que tracten el dos principals problemes identificats en aquest procés: com gestionar els resultats de risc per a prioritzar potencials inversions en seguretat i com el models de risc han de considerar la incertesa per a orientar a la presa de decisions.

En primer lloc, es mostra com el indicadors de reducció de riscs son una ferramenta útil i eficaç per a obtindré seqüències de priorització de potencials mesures de reducció de risc, especialment en la gestió conjunta de grans grups de preses. Per això, els diferents indicadors per a la gestió de la seguretat de preses son avaluats, analitzant la seua relació amb els principis d'eficiència i equitat.

En segon lloc, es proposa considerar la incertesa natural i la incertesa epistèmica de forma independent dintre del models quantitatius de risc per a preses, seguint les recomanacions d'altres industries. En particular, es proposa un procediment per a separar el dos tipus d'incertesa en el anàlisis del fall per lliscament en preses de gravetat.

Finalment, el dos punts es combinen per a proposar índexs que analitzen la influència de la incertesa epistèmica sobre les seqüencies de priorització de mesures obtingudes amb els indicadors de reducció de risc, y per tant, sobre la presa de decisions. D'aquesta forma, aquests índexs permeten analitzar la necessitat de realitzar acciones per a reduir la incertesa, como assajos, sondejos geotècnics o estudis de detall.

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1 Introduction

1.1 Motivation of research

Dams are critical hydraulic infrastructures whose failure would entail serious consequences for community safety, from economic damage to even loss of life. There is always a probability associated with critical infrastructure failure, even if it might be very low. Thus, since there are always possibilities for adverse consequences to happen there is always an associated risk.

There is nowadays a trend towards seeing dam safety as an active and ongoing management process rather than a static and deterministic statement. Tools such as risk analysis can be useful to help owners make decisions. Risk assessment helps engineers to understand uncertainties in critical infrastructures, and provides a logical process of identifying hazards, evaluating system response and vulnerabilities associated to each hazard, and assessing the effectiveness of risk reduction measures. For this reason, in recent years, risk assessment techniques have been developed worldwide and applied in the dam industry to inform safety governance (ANCOLD 2003; ICOLD 2005; USACE 2014).

In this context, the Research Institute of Water and Environmental Engineering (IIAMA) in the Universitat Politècnica de València (UPV) has leaded the application of risk analysis techniques to inform dam safety governance in Spain. One of the main achievements of this group was the publication of the SPANCOLD Guidelines on Risk Analysis Applied to Management of Dam Safety (SPANCOLD 2012), which provided a methodology to develop quantitative risk models to analyze, asses and manage dam safety.

The author of this thesis has worked for 7 years in the dam safety field, first within this research group of the UPV and later as CTO of iPresas (a spin-off company of UPV). During these years, he has worked in the application of risk analysis techniques to support dam safety management in more than 40 dams at national and international scale, owned by public and private entities.

Despite of the contextual information provided above, the application of risk analysis to dam safety management is way more complex than it may sound, observing different theoretical and practical difficulties during these years. For this reason, the author has focused this research in the two main difficulties found during these analyses:

- Filling the gap between quantitative results obtained from risk models and practical recommendations about prioritization of safety investments following risk reduction principles. This difficulty is especially important when a portfolio with many dams is analyzed since many quantitative risk results are obtained.

- The treatment of uncertainty within quantitative risk models, in order to analyze the effect of uncertainty reduction measures (tests, surveys, numerical models…) in comparison with risk reduction measures.

In conclusion, this thesis is focused on how risk results can be used to inform dam safety investments in many different contexts, providing methods and numerical indicators to ensure that quantitative risk results can be handled and are useful for decision makers.

1.2 Objectives

The main objective of this thesis is improving risk-informed dam safety governance by introducing methods and metrics that provide useful information to setting out and prioritize safety measures. Hence, this thesis is focused in the step between obtaining quantitative risk results and using them to inform dam safety management.

The specific objectives of this research are:

- Reviewing existing risk reduction indicators and their relation with risk reduction principles (efficiency and equity).
- Showing the utility of risk reduction indicators to manage quantitative risk results in complex systems, obtaining prioritization sequences of many alternatives of investment.
- Analyzing the suitability of a new risk reduction indicator (EWACSLS) that combines equity and efficiency principles.
- Researching on how natural and epistemic uncertainty has been separated in other industries, in order to analyze how it can be made in the different parts of dam risk models.
- Developing a procedure to separate natural and epistemic uncertainty in fragility analyses that populate risk models in dams. This procedure is particularized for the sliding failure mode of gravity dams.
- Proposing new metrics to quantify the effect of epistemic uncertainty in prioritization sequences of investments, in order to consider the convenience of conducting additional uncertainty reduction actions, like site tests, surveys or more detailed analysis, in a fair competition with structural fixes.

2 Publications

This thesis is a compendium of research papers. It includes three articles published in peer-reviewed journals indexed in the Journal Citations Report (JCR), one sent to one of these journals and one paper published in Congress Proceedings. They are included in the Annexes of this document and they are the following:

- Adrián Morales-Torres, Armando Serrano-Lombillo, Ignacio Escuder-Bueno, and Luis Altarejos-García. 2016. "The Suitability of Risk Reduction Indicators to Inform Dam Safety Management." *Structure and Infrastructure Engineering* 12 (11): 1465–76. doi:10.1080/15732479.2015.1136830. Impact Factor in 2015: 1.202; Q2. **Annex 1**.
- A. Serrano-Lombillo, A. Morales-Torres, I. Escuder-Bueno, and L. Altarejos-García. 2013. "Review, Analysis and Application of Existing Risk Reduction Principles and Risk Indicators for Dam Safety Management." In Proceedings of 9th ICOLD European Club Symposium. Sharing Experience for Safe and Sustainable Water Storage. Venice (Italy). 10th-12th April 2013. **Annex 2**.
- Armando Serrano-Lombillo, Adrián Morales-Torres, Ignacio Escuder-Bueno, and Luis Altarejos-García. 2016. "A New Risk Reduction Indicator for Dam Safety Management Combining Efficiency and Equity Principles." Structure and Infrastructure Engineering. doi:10.1080/15732479.2016.1245762. Impact Factor in 2015: 1.202; Q2. **Annex 3**.
- Adrián Morales-Torres, Ignacio Escuder-Bueno, Luis Altarejos-García, and Armando Serrano-Lombillo. 2016. "Building Fragility Curves of Sliding Failure of Concrete Gravity Dams Integrating Natural and Epistemic Uncertainties." Engineering Structures 125: 227–35. doi:10.1016/j.engstruct.2016.07.006. Impact Factor in 2015: 1.893; Q1. **Annex 4**.
- Adrián Morales-Torres, Ignacio Escuder-Bueno, Armando Serrano-Lombillo and Jesica T. Castillo Rodríguez. 2016. "Dealing with epistemic uncertainty in risk-informed decision making for dam safety management." Paper sent to Risk Analysis in October 2016 and currently under review. Impact Factor in 2015: 2.225; Q1. **Annex 5**.

3 Results and discussion

3.1 Introduction

In critical infrastructures safety management, risk is the combination of three concepts: what can happen (infrastructure failure), how likely is it to happen, and what are its consequences (Kaplan 1997). Following this definition, in the dam safety field, risk is usually quantified with the following equation (Luis Altarejos-García et al. 2012):

$$Risk = \int P(loads) \cdot P(response|loads) \cdot C(loads, response) \quad \textit{Eq. 1}$$

Where the integral is defined over all the events under study, *P(loads)* is the probability of the different load events, *P(response|loads)* is the conditional probability of the structural response for each load event and *C(loads,response)* are the consequences of the system response for each load event.

In the dam safety field, the system response analyzed is the dam failure. Consequences can be introduced in economic terms to obtain **economic risk** or in terms of potential loss of life, to obtain **societal risk** (Morales-Torres, Serrano-Lombillo, et al. 2016). If consequences are expressed in terms of loss of life, **FN curves** can be derived to represent the relation between loss of life and exceedance probability. The area under these curves is equivalent to the societal risk (Vrijling and van Gelder 1997).

These terms of the equation are usually analyzed independently and they can be combined within a quantitative risk model to compute dam failure risk. Risk models are commonly created through event trees (SPANCOLD 2012; USBR and USACE 2015), which analyze the different ways in which a dam can fail (failure modes) calculating their associated probabilities and consequences.

The first part of this thesis is focused on how risk reduction indicators can be very suitable to manage a high number of risk results, which is usual when a large portfolio of dams is managed. These indicators are based on equity and efficiency principles and they can be used to obtain prioritization sequences of potential risk reduction measures. This prioritization procedure is contextualized within the Tolerability of Risk (TOR) framework, which was set out by UK's (HSE 2001) for risk evaluation and management and has been widely used in dam safety (ANCOLD 2003; SPANCOLD 2012; USACE 2014; USBR 2011).

A detailed review of existing risk reduction indicators is made and their suitability is analyzed applying them to prioritize 93 measures in a portfolio of 27 dams. In addition, the performance of a new indicator that combines equity and efficiency (EWACSLS) is analyzed. Section 3.2 summarizes these findings, which are described in detail in **Annex 1** (Morales-Torres, Serrano-Lombillo, et al. 2016), **Annex 2** (A. Serrano-Lombillo et al. 2013) and **Annex 3** (Armando Serrano-Lombillo et al. 2016).

The second part of this thesis deals with uncertainty and how it can be introduced in quantitative risk models. Many authors have identified two distinctive categories or sources of uncertainty (Ferson and Ginzburg 1996; Hartford and Baecher 2004; Hoffman and Hammonds 1994; SPANCOLD 2012):

- **Natural uncertainty or randomness:** produced by the inherent variability in the natural processes. It includes the variability along time of phenomena that take place in a precise point of the space (temporal variability) or the variability across the space of phenomena that take place in different points but simultaneously (spatial variability).

  An example of this kind of uncertainty is the variability of the loads that the structure has to withstand, for instance, the variability in the potential intensity of earthquakes. Another example is the strength's variability of the foundation where the structure stands. This type of uncertainty cannot be reduced, though it can be estimated.

- **Epistemic uncertainty:** resulting from lack of knowledge or information about the analyzed system. The more knowledge is available about a structure, the more this type of uncertainty can be reduced. On the other hand, it is usually very difficult to estimate or quantify this uncertainty.

  An example of this type of uncertainty can also be found in the strength of the foundation. The information about the foundations may be limited so the parameters used to characterize its resistance are estimated though probing and exploration. With more resources, the foundation can be better characterized and the epistemic uncertainty is reduced, although the natural variability of the foundation may still be very significant.

The distinction between natural and epistemic uncertainty takes added importance for a quantitative risk analysis in complex structures (Baraldi and Zio 2008). In this context, natural uncertainty is usually related to the occurrence of events that can produce the structural failure and the randomness of the structure's resistant behavior for the load produced by the events. In contrast, epistemic uncertainty is mainly focused on the lack of knowledge of the loading events, the failure mechanisms, the structure's resistance parameters and the consequences produced by the failure.

Section 3.3 explains how epistemic and natural uncertainties can be introduced separately within quantitative risk models, following the recommendations of other industries. For instance, a procedure is developed to separate both types of uncertainty in a fragility analysis of the sliding failure mode for gravity dams.

This section summarizes the findings described in detail in **Annex 4** (Morales-Torres, Escuder-Bueno, Altarejos-García, et al. 2016) and **Annex 5** (Morales-Torres, Escuder-Bueno, Serrano-Lombillo, et al. 2016).

Finally, **the third part of the thesis** combines the other two parts and analyzes how epistemic uncertainty can influence decision making. As explained in Section 3.4, different metrics are proposed to analyze the effect of epistemic uncertainty variations on the prioritization sequences obtained by risk reduction indicators. These metrics provide very useful information for decision making since they analyze the need for uncertainty reduction measures, which can be necessary before investing in risk reduction measures. Hence, this thesis proposes metrics to deal with uncertainty in quantitative risk analysis for dams, which is one of the main identified barriers for smart risk governance (Escuder-Bueno and Halpin 2016). These findings are described in detail in **Annex 5** (Morales-Torres, Escuder-Bueno, Serrano-Lombillo, et al. 2016).

The three parts of this thesis and their relations are summarized in Figure 1.

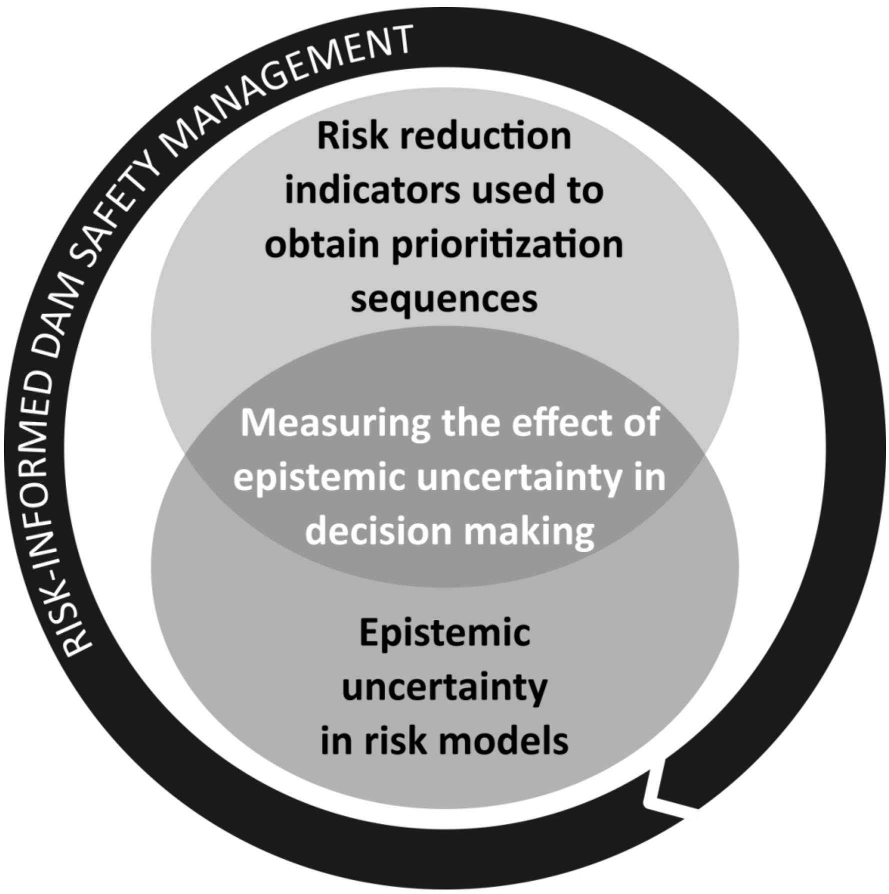

Figure 1. Relation between the three parts of this thesis.

3.2 Risk reduction indicators to inform dam safety management

3.2.1 Risk reduction principles

The key part of the risk analysis process is decision-making for risk management. Decisions are made after considering possible alternatives and analyzing their effect on infrastructure risk. Generally, two principles are recommended to guide this decision-making process (HSE 2001; ICOLD 2005; USACE 2014):

- **Equity:** In the context of critical infrastructure safety management, this principle arises from the premise that all individuals have unconditional rights to certain levels of protection (Le Guen 2010). This principle is applied through the **individual risk**, which can be defined as the probability that at least one person dies as a result of the dam's failure (SPANCOLD 2012).

  Hence, individual risk tolerability recommendations seeking a certain level of protection for every individual of the population are related to the principle of equity. According to (HSE 2001), the application of this principle should prevail when individual risk is above the recommended value of tolerability. There are numerous recommendations to establish this value, varying according to the activity or industry under study. Some examples for flood risk can be seen in the Dutch regulations (Vrijling, van Hengel, and Houben 1995) and in the guidelines by (USACE 2014).

- **Efficiency:** This principle arises from the fact that society possesses limited resources which must be spent in the most efficient way. When considering several risk reduction measures, the one producing a higher risk reduction at a lower cost (the one that optimizes expenditure) should generally be chosen first. This is usually the prevailing principle when risk is tolerable (HSE 2001). In this research, a distinction between two types of efficiency is suggested, depending on the targeted risk:
  - **Societal efficiency:** When the target risk to be reduced is societal risk.
  - **Economic efficiency:** When what is analyzed is economic risk reduction, that is, the searched strategy is the most advantageous from an economic point of view. According to some authors (Bowles 2001), this type of efficiency should only prevail when the infrastructure complies with tolerability recommendations.

These two principles can conflict, since what can be an optimal measure from the equity point of view may not be so from the efficiency point of view and vice versa. This dilemma between efficiency and equity is not only restricted to risk analysis and safety management, but it also occurs in many other fields related with decision making in the public sector. For instance, in general public investments (Albalate, Bel, and Fageda 2012; Blackorby and Donaldson 1977; Yamano and Ohkawara 2000), the health sector (Bleichrodt 1997; Dolan 1998), the transport sector (Joshi and Lambert 2007) the education sector (Dundar and Lewis 1999; De Fraja 2001) and the environmental sector (Linnerooth-Bayer and Amendola 2000; Swisher and Masters 1992). Though in these cases the definitions of equity and efficiency are slightly different, the philosophy and the dilemma between both concepts remain the same. Most of these authors highlight the importance of combining efficiency and equity in an integrated management of public resources.

3.2.2 Prioritization sequences based on risk reduction indicators and principles

When quantitative risk analysis is applied to inform safety management of portfolios of dams, a high number of results are obtained. In this context, risk reduction indicators have proved to be a useful tool to prioritize risk reduction measures (Bowles et al. 1999; Morales-Torres, Serrano-Lombillo, et al. 2016; Armando Serrano-Lombillo et al. 2016). Risk reduction indicators are numeric values obtained for each potential measure based on its costs and the risk reduction it provides and they are widely used to inform safety management in different fields (Lutter, Morrall, and Viscusi 1999; Ramsberg and Sjöberg 1997; Stewart and Mueller 2008).

In (Morales-Torres, Serrano-Lombillo, et al. 2016), a procedure is laid out to obtain prioritization sequences based on risk reduction indicators. In each step of the sequence, the measure with the lowest value of the indicator is chosen. Of course, the obtained prioritization sequence depends on the risk reduction indicator used to define it. Hence, this procedure does not intend to choose between different alternatives but to prioritize them, assuming that with enough time and resources, all of them will be implemented.

As explained in the previous paper, prioritization sequences can be represented in variation curves (Figure 2), which represent the variation of the aggregated risk in the portfolio as measures are implemented. In the X axis, annualized costs or implementation steps can be displayed while in the Y axis aggregated individual risk, societal risk or economic risk can be shown.

Depending on what is represented in each axis, the risk reduction indicator which will lead to the optimum sequence is different. The optimum sequence of the variation curve which represents aggregated societal risk versus costs will be the optimum from the societal efficiency point of view, since it represents the sequence which reduces societal risk at the lowest costs. For this reason this variation curve is called in this thesis societal efficiency variation curve. Following the same logic, the graph showing individual risk versus costs is called equity variation graph and the graph showing economic risk versus costs is called economic efficiency variation graph.

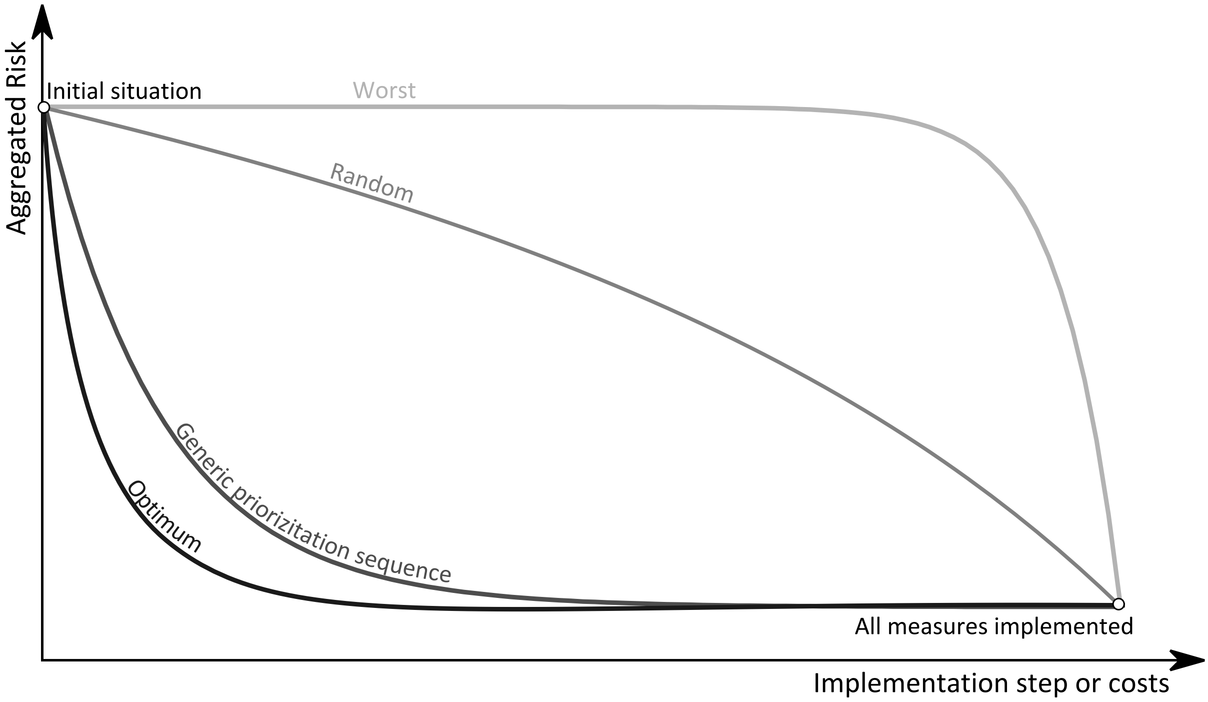

Figure 2. Generic representation of variation curves to define prioritization sequences. Source: (Armando Serrano-Lombillo et al. 2016).

In (Morales-Torres, Serrano-Lombillo, et al. 2016) existing risk reduction indicators to compare different investment alternatives are reviewed. This review comprises the dam safety field and other hazardous industries and the relation between risk reduction measures and equity and efficiency principles. In the dam safety field, two indicators are prevalent in the evaluation of risk reduction measures:

- **CSLS (Cost per Statistical Life Saved):** (ANCOLD 2003; HSE 2001) This indicator shows how much it costs to avoid each potential loss of life as a result of a dam. It is widely used to manage quantitative risk results in different fields (de Blaeij et al. 2003; Khadam and Kaluarachchi 2003; Lutter, Morrall, and Viscusi 1999; Stewart and Mueller 2008). Its value is obtained through the following formula:

$$CSLS = \frac{C_a}{r_s(base) - r_s(mea)} \qquad \textit{Eq. 2}$$

Where $r_s(base)$ is the risk expressed in loss of lives for the base case, r_s *(mea)* is the risk in lives after the implementation of the measure and C_a is the annualized cost of the measure including its annualized implementation costs, annual maintenance costs and potential changes in operation costs produced by the adoption of the measure.

CSLS compares costs with societal risk reduction, so when considering several measures, the measure with a minimal value of this indicator will be the one that employs the resources in a most efficient way. Therefore, this indicator is based on the principle of societal efficiency.

- **ACSLS (Adjusted Cost per Statistical Life Saved):** (ANCOLD 2003; Bowles 2001) This indicator has the same structure as CSLS but introduces an adjustment of the annualized cost to consider the economic risk reduction generated by the implementation of the measure. It is obtained with the following equation:

$$ACSLS=\frac{C_a-(r_e(base)-r_e(mea))}{r_s(base)-r_s(mea)} \qquad \textit{Eq. 3}$$

Where r_e *(base)* is the economic risk of the infrastructure for the base case and r_e *(mea)* is the economic risk after the implementation of the measure. As in the previous case, it is based on the efficiency principle, though for adjusted costs, so it considers both societal and economic efficiency.

Other reviewed risk reduction indicators to prioritize risk reduction measures are:

- **CBR (Cost-Benefit Ratio):** Arises from the comparison of the costs of a measure with the economic risk reduction benefits resulting from its implementation. It follows the economic efficiency principle.
- **CSFP (Cost per Statistical Failure Prevented):** Expresses how much it costs to avoid infrastructure failure for each measure. Its formulation is based on failure probability, so it follows the equity principle.
- **ACSFP (Adjusted Cost per Statistical Failure Prevented):** Has the same form as CSFP but introduces an adjustment on the annualized cost to consider the reduction of economic risk produced by the implementation of the measure.
- **Individual Risk Decrease Index (IRDI):** Used to select whichever measure produces the highest decrease in individual risk in each step in the sequence regardless of other factors. This criterion is related to equity.
- **Societal Risk Decrease Index (SRDI):** As before but minimizing societal risk. This criterion is related to societal efficiency.

- **Economic Risk Decrease Index (ERDI):** As before but minimizing economic risk. This criterion is related to economic efficiency.

3.2.3 New risk reduction indicator for combining efficiency and equity principles

Each indicator is therefore either based on the efficiency or the equity principle, but none of them takes both principles into account. For this reason, in (Armando Serrano-Lombillo et al. 2016) a new risk reduction indicator is introduced to combine equity and efficiency principles:

- **Equity Weighted Adjusted Cost per Statistical Life Saved (EWACSLS):** This indicator is computed with the following formula:

$$EWACSLS = \frac{ACSLS}{\left(\frac{\max(r_i(base),IRL)}{\max(r_i(mea),IRL)}\right)^n} \qquad \text{Eq. 4}$$

  Where *ri(base)* is the individual risk for the base case expressed in years-1, *ri(mea)* is the individual risk in years-1 after the implementation of the measure, *IRL* stands for Individual Risk Tolerability Limit and *n* is a parameter that allows assigning a higher weight to either efficiency or equity in the prioritization process. As can be observed in this equation, if the individual risk is lower than *IRL*, the only prevailing principle is efficiency (through ACSLS), since the denominator of the formula is then 1. Thus, the equity principle only modifies the value of the indicator in the cases where individual risk is above tolerability thresholds.

  The *n* parameter can be used to provide flexibility to the EWACSLS. If the value of *n* is very high, the prevailing prioritization principle is equity whereas if it is very low, efficiency prevails. Hence, once a value of *n* is set, it can be used to consistently compare an array of measures. A value of n equal to 1 seems to be a reasonable compromise between both principles.

The EWACSLS indicator allows a smooth transition between equity and efficiency principles, since the closer the individual risk is to its limit, the less weight the equity principle has. This indicator is better aligned with risk analysis principles than simply establishing a binary threshold determining whether equity should prevail or not. If this kind of binary threshold is used, only equity is taken into consideration in the non-tolerable area and only efficiency in the tolerable area, so principles are used in separated domains. The results of this approach would be more sensible to existing uncertainties in risk estimation, since small changes in individual risk could produce changes in the prevailing principles. Risk evaluation and governance should not be about being above or under a threshold, but about informing decision making combining both principles in order to reduce risk as much as possible.

Figure 3 uses a Venn diagram to visualize the relationship between all the reviewed indicators and principles. As can be observed in this figure, EWACSLS is the only indicator that is related with the three risk reduction principles.

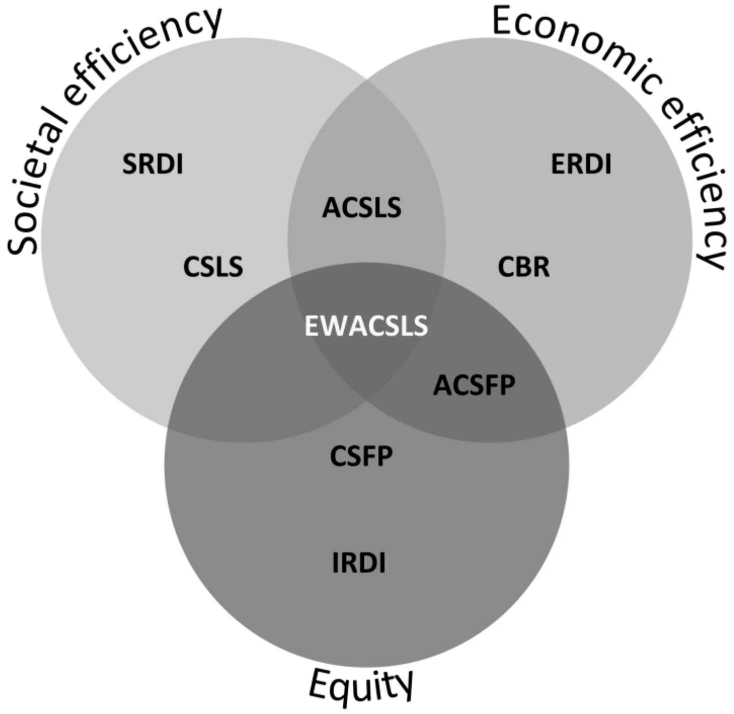

Figure 3. Venn diagram that shows the relationship between risk reduction indicators and efficiency and equity principles. Source: (Armando Serrano-Lombillo et al. 2016).

3.2.4 Assessment of measures implementation sequences

Finally, in order to analyze how close prioritization sequences are to a risk reduction principle, three indexes based on variation curves were developed in (Morales-Torres, Serrano-Lombillo, et al. 2016). These indexes are called CTB (closeness to the best) indexes and they are directly related to equity, societal efficiency and economic efficiency. For instance, in the equity variation graph, the prioritization sequences closer to the optimum will result in higher values of the CTB societal efficiency index. The same logic can be applied to equity and economic efficiency. These indexes allow evaluating any prioritization sequence of risk reduction measures against the general risk reduction principles, so they can be used to analyze the relation between risk reduction principles and principles.

CTB indexes have a graphical interpretation following Figure 3. The numerator of the suggested indexes is equal to the area under the variation curve whereas the denominator is equal to the total area of the rectangle defined by the initial and final points of the sequence (Total area). Thus, CTB can be calculated with the following equation:

$$CTB = 1 - \frac{Prioritization\ area}{Total\ area} \qquad Eq.\ 5$$

The value of this index is 0 when the area under the variation curve is equal to the total area of the rectangle and its value is 1 when the area under the curve is null.

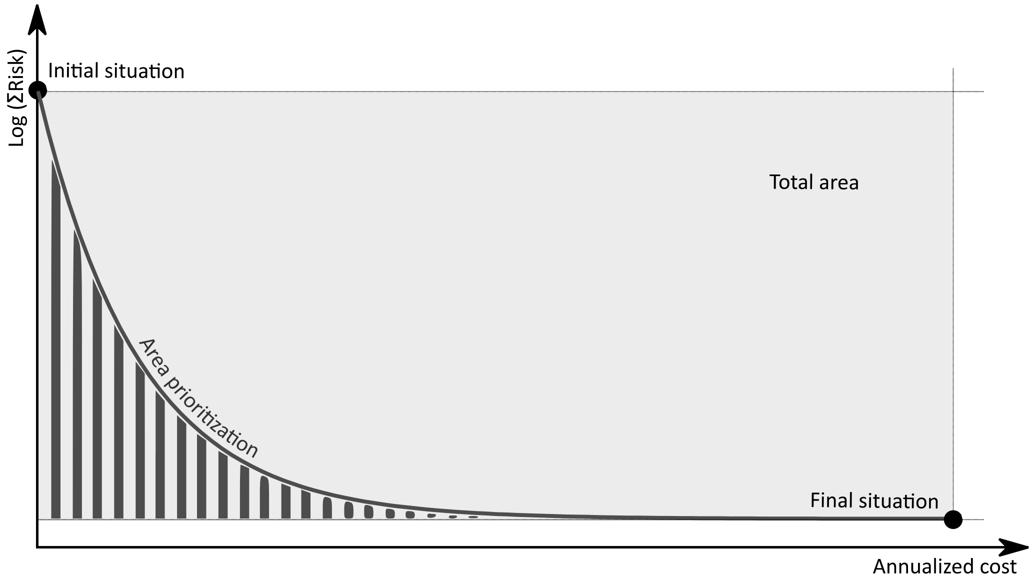

Figure 4. Definition of areas in variation curves in order to interpret CTB. Source: (Morales-Torres, Serrano-Lombillo, et al. 2016).

Hence, societal efficiency variation curves are used to evaluate Societal Efficiency CTB Index, equity variation curves are used to evaluate Equity CTB Index and economic efficiency variation curve are used to obtain Economic Efficiency CTB Index.

3.2.5 Case study: A portfolio of 27 dams in Spain

In (Morales-Torres, Serrano-Lombillo, et al. 2016; A. Serrano-Lombillo et al. 2013; Armando Serrano-Lombillo et al. 2016), risk reduction indicators were applied to prioritize safety investments in a real portfolio of 27 dams in Spain. These dams belong to the same owner, which defined a list of 93 safety measures to be implemented in the dams in the following years. It is a very heterogeneous portfolio of dams including structures of different typology (15 concrete gravity dams, 4 small diversion dams, 3 embankments, 3 double-curve arch dams and 2 single-curve arch dams), size (from 100.6 m to 11.6 m height), construction year (from 1923 to even one currently under construction) and reservoir volume (from 641 hm3 to 0.2 hm3).

The starting point for this case study was the results obtained in a Quantitative Risk Analysis performed on each dam. As part of the analysis process, risk models were set up with iPresas software (iPresas 2014) for each dam. These risk models analyze the different ways in which a dam can fail (failure modes) calculating their associated probabilities and consequences. Input data in the risk models were elaborated during three years and they are the result of dams technical documents, working group sessions and numerical models. Detailed procedures followed to develop these risk models can be found in (L. Altarejos-García, Escuder-Bueno, et al. 2012; Ardiles et al. 2011; A. Serrano-Lombillo, Fluixá-Sanmartín, and Espert-Canet 2012; A. Serrano-Lombillo, Morales-Torres, and García-Kabbabe 2012). Figure 5 shows an example of one of the risk models.

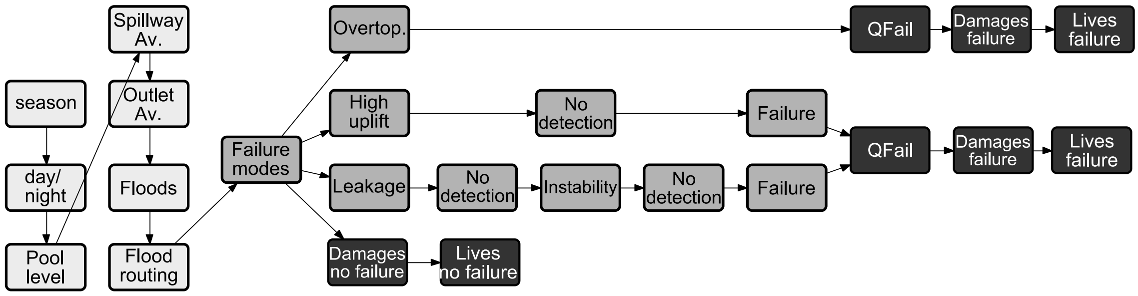

Figure 5. Quantitative risk model of one of the case study dams. Source: (Armando Serrano-Lombillo et al. 2016).

The 93 measures planned to improve dams safety include 38 structural measures and 55 non-structural measures. Proposed measures are not general measures for all the dams: each of them is planned and tailored to be applied only in one dam. Some examples of the planned structural measures are increment of spillway capacity or improvements in the gates reliability, the foundation conditions or the dam body imperviousness. The non-structural measures are mainly focused on developing Emergency Action Plans and risk awareness campaigns, improving the monitoring systems and introducing more restrictive freeboards in the reservoirs.

The high number of risk reduction measures to be prioritized justifies the use of risk reduction indicators to define these sequences more efficiently, since there are $93! \approx 10^{144}$ possible sequences of measures to be considered. In order to illustrate it, a sequence corresponding to a random average case was calculated to compare with the implementation sequences obtained from the application of the risk reduction indicators. In order to obtain this average, 1,000 random sequences were obtained, choosing the measure randomly in each step. The random average case was then determined by obtaining the average risk variation of all of them for each implementation step. Figure 6 compares these sequences with the sequence obtained choosing in each step the measure with a lower value of the EWACSLS indicator. As can be observed, the sequence obtained with EWACSLS performs much better than any of the random sequences, since it reduces risks with lower costs. It should be remarked that the Optimum sequence shown in Figure 6 is only the best for this type of variation graph (with the societal risk represented in the Y axis and annualized cost in the X axis) since no sequence of measures that is optimum for all the types of variation graphs and principles exists. In this variation graph, this sequence is obtained using the CSLS indicator.

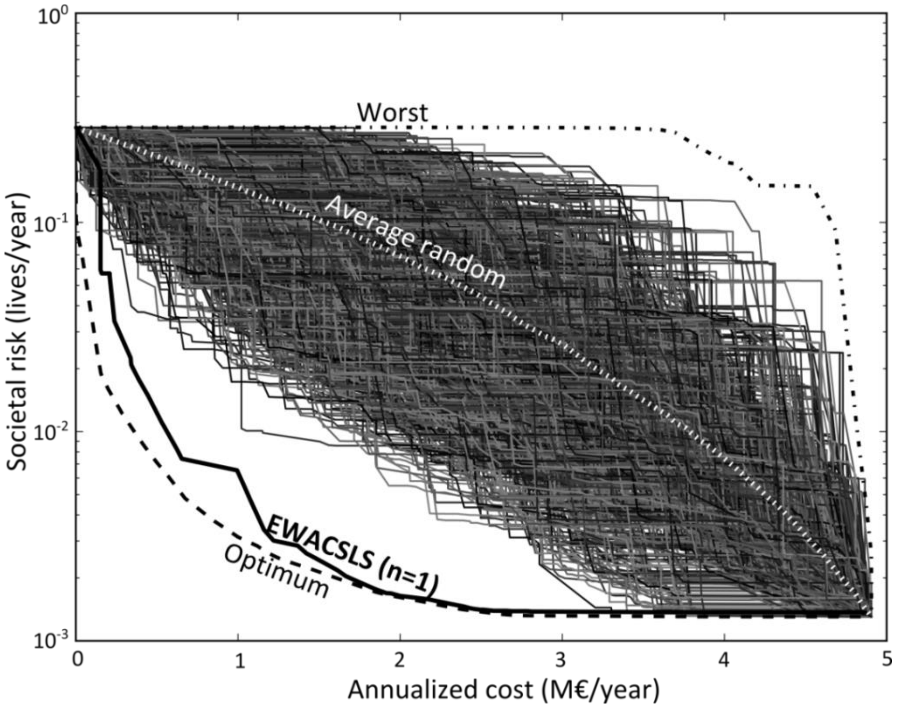

Figure 6. Comparison of the results of the 1000 randomly calculated cases with the sequence obtained with EWACSLS indicator in the societal efficiency variation curve. Source: (Armando Serrano-Lombillo et al. 2016).

Different measure implementation sequences were obtained by using all of the risk reduction indicators previously defined. When doing these calculations, individual risk was assumed to be equal to failure probability. This is a usual hypothesis in large dams (USBR 2011) as the ones studied in this case, since dam failure would almost certainly result in at least one fatality.

Incremental consequences were used to calculate societal and economic risks. Incremental consequences are incremental losses or damage, which dam failure might inflict on upstream areas, downstream areas, or at the dam, over and above any losses which might have occurred for the same natural event or conditions, had the dam not failed (ANCOLD 2003). Risk is then known as incremental risk and is usually employed in dam safety (ANCOLD 2003; USACE 2014).

Next, using all the presented indicators, different measure implementation sequences were obtained for the set of dams under analysis. Figure 7 shows equity, societal efficiency and economic efficiency variation curves for the different calculated indicators.

According to (USACE 2014), the proposed tolerability limit for individual risk used to compute risk reduction indicators is 10^{-4}. In addition, a sequence combining ACSFP (with failure probabilities higher than 10^{-4}) and ACSLS (with failure probabilities lower than 10^{-4}) was also calculated. This sequence is labelled ACSLS/ACSFP in the figures.

In each variation curve the indicator that produces a better sequence (more significant risk reduction at a lower cost) is different. In the case of the societal efficiency curve, the optimal sequence is given by the indicator CSLS, for the economic curve, it is ECBR and in the case of equity, CSFP. Additionally, the worst implementation sequence was defined for each case, choosing at each step the measure with the highest value of the indicator that produces the optimal sequence. These sequences are also shown in Figure 7.

The CTB indexes defined in previous section were then used to numerically analyze the goodness of the implementation sequences according to each prioritization principle. The indicators that produced better values of societal efficiency were CSLS and ACSLS. The indicators producing higher economic efficiency were ECBR and ACSFP. Finally, the indicators producing better equity values were CSFP and ACSFP. In order to compare graphically how societal efficiency and equity principles are addressed for each indicator, the CTB indexes obtained for both principles have been represented in Figure 8.

EWACSLS, was not the optimum in any of the ratios, but had a very good score in all of them, being the most balanced of all of the indicators under study. Furthermore, as observed in Figure 8, with EWACSLS it is possible to vary a measure implementation sequence giving more or less relative weight to the principles of efficiency or equity thanks to parameter n, while still obtaining values of CTB indexes that are close to the optimal ones. As can be seen in figures 10 and 11, the dotted line of EWACSLS varies between ACSLS (n = 0) and the ACSFP/ACSLS combination (n -> ∞), which is a logical consequence of its mathematical formulation.

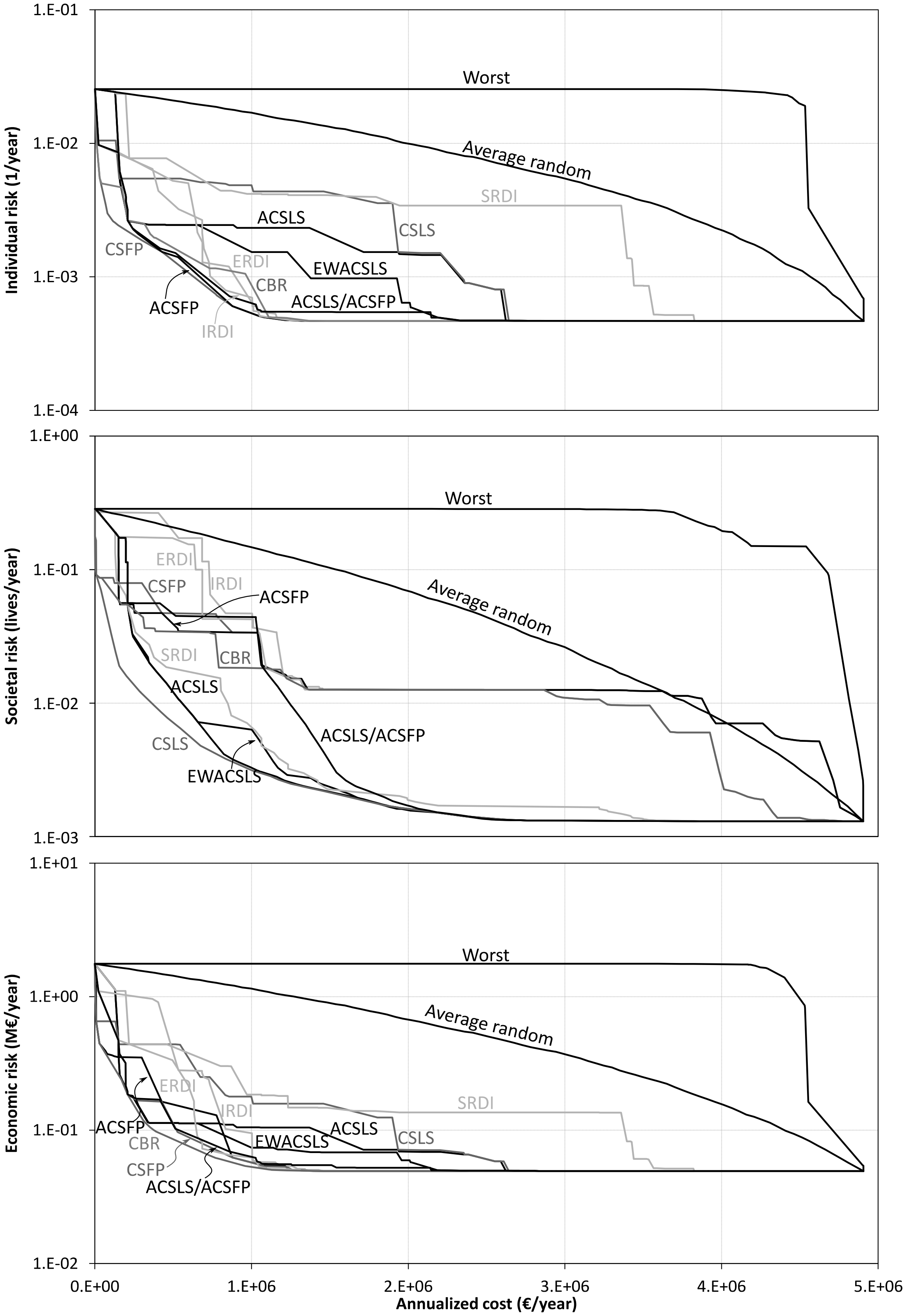

Figure 7. Implementation sequences for different risk reduction indicators represented in the variation curves for equity, societal efficiency and economic efficiency principles. Adapted from: (Morales-Torres, Serrano-Lombillo, et al. 2016; Armando Serrano-Lombillo et al. 2016).

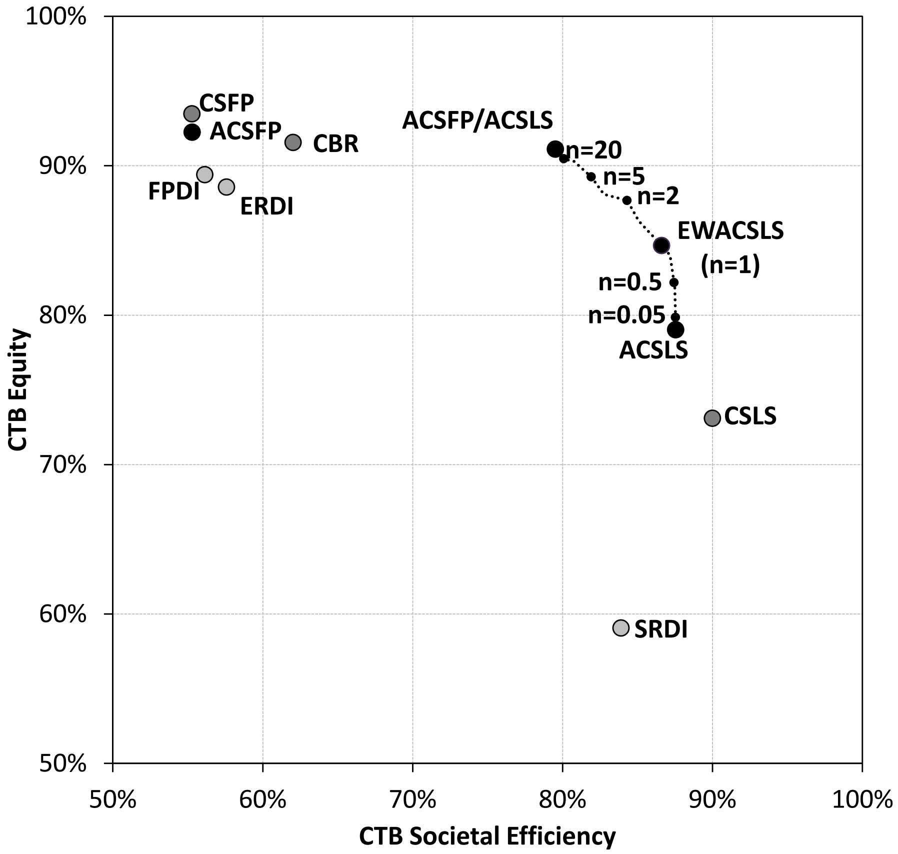

Figure 8. Comparison between societal efficiency CTB and equity CTB for EWACSLS and the other risk indicators. Source: (Armando Serrano-Lombillo et al. 2016).

In conclusion, as demonstrated with this case study, the developed procedure based on risk reduction principles and its indicators, allows obtaining and assessing measure implementation sequences in a clear and simple way from quantitative risk results. This procedure reduces significantly the required computations to obtain an optimum prioritization sequence in complex portfolios with many proposed measures. It also allows tracking the impact of different principles, to combine them and to compare them.

In practice, each critical infrastructure operator will choose the principles and tolerability limits that reflect its values and objectives more adequately. Besides, management of critical infrastructure safety actions can incorporate many factors of administrative, societal and economic order, difficult to quantify and that might condition decision-making. Within this context, measure implementation sequences based on risk results provide valuable information to decision-making and in some cases can be an input to a more global multi-criteria analysis.

3.3 Epistemic uncertainty in risk models for dams

3.3.1 Levels of addressing uncertainty in quantitative risk analysis

In risk models for dams, natural and epistemic uncertainties are not usually introduced separately. They are usually mixed in the probability input data introduced for the structural response with a mean conditional failure probability for each loading state (Morales-Torres, Escuder-Bueno, Altarejos-García, et al. 2016). This approach is called first-order probabilistic risk analysis (E. Paté-Cornell 2002) and it is the most common approach in risk-informed dam safety management (ANCOLD 2003; SPANCOLD 2012; USBR and USACE 2015).

As a result of applying Equation 1 in an event tree, a single value of failure probability and risk is obtained. If consequences are expressed in terms of loss of life, FN curves can be derived to represent the relation between loss of life and exceedance probability. The area under these curves is equivalent to the societal risk (Vrijling and van Gelder 1997).

First-order probabilistic risk analysis represents Level 4 of complexity in the classification developed by (M. E. Paté-Cornell 1996). There is a higher level of complexity to fully represent both types of uncertainty (Level 5), called second-order probabilistic risk analysis. In this level, epistemic and natural uncertainties are introduced separately in the risk model, defining probability distributions for input data in the risk equation.

In order to carry out calculations in Level 5 models, the two types of uncertainty can be addressed using a two-loop Montecarlo analysis (Baraldi and Zio 2008). In the upper loop, random variables with epistemic uncertainty are sampled. These sampled values are used to compute risk in the lower loop. Another option can be to combine epistemic uncertainty variables sampling in the upper loop of Montecarlo analysis with event trees. Hence, a risk result is obtained for each group of sampled values with the event tree (Luis Altarejos-García et al. 2014; Chauhan and Bowles 2001). In both approaches, when risk results are ordered, a risk probability distribution is obtained.

Hence, in a second-order probabilistic risk analysis, a risk probability distribution and a family of FN curves are obtained instead of a single value and curve, as explained in (Chauhan and Bowles 2001; E. Paté-Cornell 2002). The spread of risk probability distribution and the family of FN curves thus represents the degree of epistemic uncertainty in the risk assessment. In Figure 9, the type of risk results and risk representation are compared for first-order and second-order probabilistic risk analyses. Second-order probabilistic risk analysis is more common in other industries like the nuclear industry (EPRI 1994).

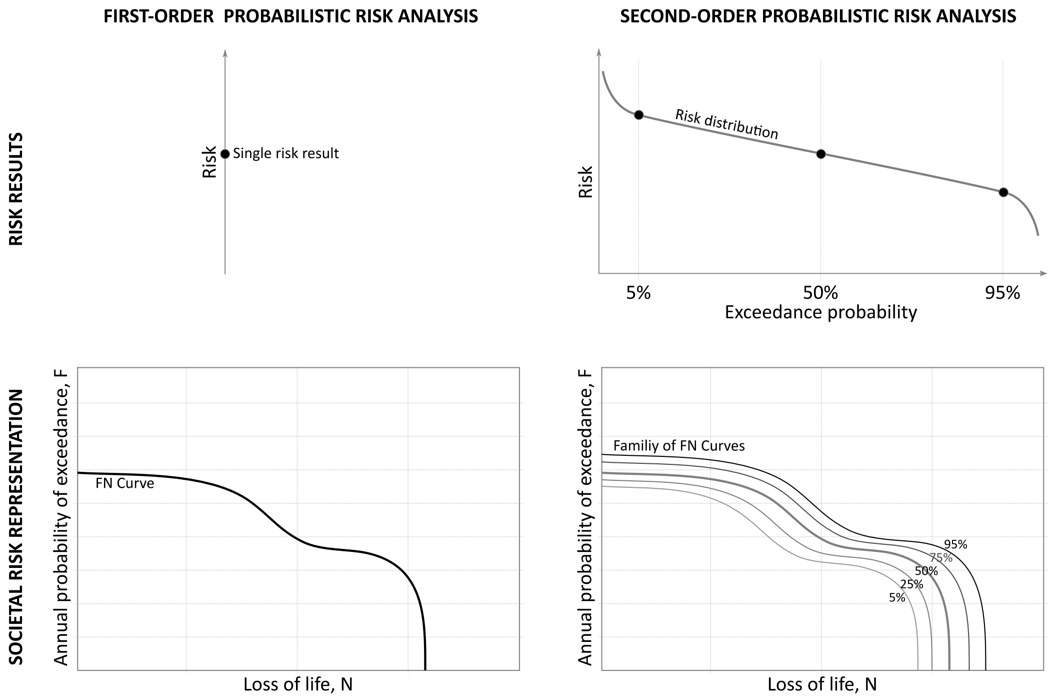

Figure 9. Comparison of risk results and risk representation between first-order and second-order probabilistic risk analysis. Source: (Morales-Torres, Escuder-Bueno, Serrano-Lombillo, et al. 2016).

3.3.2 Dealing with epistemic uncertainty in quantitative risk models

In recent years, different research studies have been developed to characterize epistemic uncertainty in input data of quantitative risk analysis for dams. As explained above, the separation of epistemic and natural uncertainties in input data is the first step for a second-order risk analysis. Following the three terms of the risk equation (Equation 1), the existing approaches that can be followed to make this separation are (Morales-Torres, Escuder-Bueno, Serrano-Lombillo, et al. 2016):

- **Probability of loading:** This part of the equation typically makes reference to the probability of severe flood events and their subsequent reservoir elevations (hydrological scenario) or severe seismic events (seismic scenario).

  In hydrological scenarios, in general a probability distribution for reservoir elevations is introduced in the risk model obtained from the probability of flood events, probability of previous pool levels in the reservoir and probability of availability of outlet works (Carvajal et al. 2009; A. Serrano-Lombillo, Fluixá-Sanmartín, and Espert-Canet 2012).

  In order to separate both types of uncertainty, main epistemic uncertainties in the rainfall-runoff and flood routing process should be characterized. Different families of inflow hydrographs in the reservoir can be obtained based on a parametric rainfall-runoff analysis (Apel et al. 2004) and they can be combine with previous pool levels and gates availability to obtain a family of probability distributions for reservoir elevations (or volumes) in the reservoir (Bianucci et al. 2013). The spread of this family of curves represents the degree of epistemic uncertainty in the hydrological loading.

In seismic scenarios, epistemic and natural uncertainties of seismic loading could be separated as it is made in the nuclear industry (EPRI 1994). Hence, different families of seismic events could be generated to compute failure probability instead of a single Annual Exceedance Probability-Ground acceleration curve (Chauhan and Bowles 2001).

- **Probability of system response:** This part of the equation is addressed through **fragility curves**, which represent a relationship between conditional failure probability and the magnitude of loads that produce failure. As explained in the following section, in (Morales-Torres, Escuder-Bueno, Altarejos-García, et al. 2016), a procedure is introduced to perform fragility analysis for dams in order to identify and track natural and epistemic uncertainty separately. As a result of this procedure, a family of fragility curves is obtained to characterize the sliding failure, as shown in Figure 10. The spread of this family is an indicator of the influence of the epistemic uncertainty in the results.

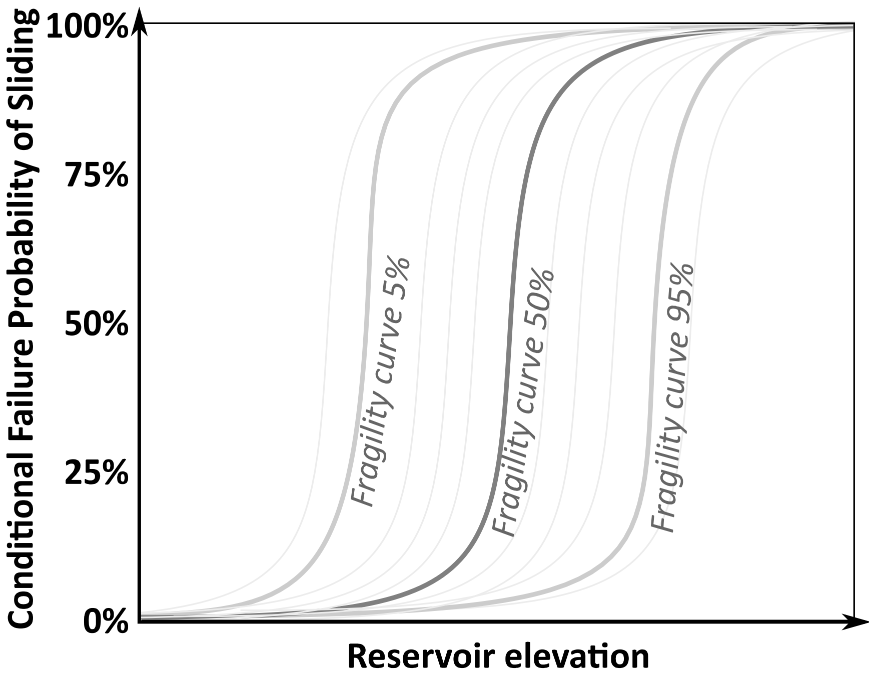

Figure 10. Example of family of fragility curves for sliding failure mode. Source: (Morales-Torres, Escuder-Bueno, Serrano-Lombillo, et al. 2016).

The same concepts were followed to obtain a family of fragility curves for other failure modes in dams, like embankment instability (Luis Altarejos-García et al. 2014) and overtopping (Chauhan and Bowles 2001).

- **Dam failure consequences:** In first-order probabilistic risk analysis, a single value of economic consequences or loss of life is used in each branch of the event tree to compute risk. In order to include epistemic uncertainty, a probability distribution of consequences could be introduced in each branch of the event tree. These probability distributions can be obtained based on epistemic uncertainties in hydraulic models (L. Altarejos-García, Martínez-Chenoll, et al. 2012) and warning and evacuation procedures (Aboelata, Bowles, and McClelland 2003; Chauhan and Bowles 2001).

3.3.3 Procedure for sliding fragility analysis dealing with epistemic uncertainty

In order to illustrate how epistemic and natural uncertainty input data can be separated in input data for quantitative risk models, in (Morales-Torres, Escuder-Bueno, Altarejos-García, et al. 2016) a procedure was presented to build fragility curves for the sliding failure mode of concrete dams integrating natural and epistemic uncertainties. This procedure adapts the fragility analysis methodology developed in the nuclear industry (EPRI 1994; Kennedy and Ravindra 1984) to the dam safety field.

This procedure develops fragility analysis, which accounts for both types of uncertainty, being focused in the second term of Equation 1. The procedure is focused on applying this procedure for the sliding failure mode of concrete gravity dams, although it can be used for fragility analysis of other structural failure modes.

Sliding failure mode was selected since sliding produced by insufficient shear strength in the foundation is the most common cause of failure of concrete gravity dams according to the International Commission on Large Dams (ICOLD 1995). For this reason, regulatory rules and guidelines in most countries address this failure mode.

The proposed procedure includes the following steps:

- **Step 1.** Define the mathematical or numerical model that simulates the physical problem. As explained in (Luis Altarejos-García et al. 2012), different models can be used to analyze sliding failure, form simple limit equilibrium models to complex non-elastic models. The selection will depend on the complexity of the problem analyzed and the quantity and quality of data available. The performance of the model selected is also a source of epistemic uncertainty that should be analyzed in Step 8.

- **Step 2.** Define the loading range and the number of loading cases analyzed to estimate the fragility curve. For the sliding failure mode, loadings are usually represented by the reservoir elevation, since water pressure and uplift are the driving forces for this failure.

- **Step 3.** The working team has to assess which variables of the model will be considered as subjected to none or very low uncertainty, and which variables have necessarily to be treated as random. Typically, for the sliding failure mode, most of the uncertainty lies on the foundation strength and the magnitude of pore water pressures in the foundation soils, including the soil along rock discontinuities, or uplift pressures along such rock discontinuities.

- **Step 4.** Two different distributions should be defined for each random variable: one for natural uncertainty and one for epistemic uncertainty. Mean values, standard deviations and probability distribution should be estimated, based on available data. In order to follow the conceptual framework developed by (EPRI 1994), it is proposed that both distributions should have the same mean, while the standard deviations and the probability distribution will depend on the natural and epistemic uncertainty. As explained in Step 7, the distribution defined for the epistemic uncertainty is a distribution of means of the random variables. Typically used probability distribution, include uniform, normal, log-normal, triangular, and beta distributions.

- **Step 5.** Select the reliability method that will be used in the model to estimate failure probability. Some examples of these methods are First Order Second Moment (FOSM), Taylor's Method, Point Estimate Method (PEM), Advanced Second Moment (ASM) Hasofer-Lind Method and Monte Carlo Method (Luis Altarejos-García et al. 2012; Cornell 1971; Hasofer and Lind 1974; Rosenblueth 1981). Different reliability methods can be chosen for epistemic and natural uncertainty.

- **Step 6.** For each loading case, compute the conditional failure probability using the selected reliability method for the natural uncertainty. In this step, values of the random variables are selected based on the chosen reliability method (Step 5) and the probability distributions defined for the natural uncertainty (Step 4). Therefore, different computations of the numerical model (Step 1) are made with these selected values to estimate failure probability.

  When failure probability is represented versus loading range, the fragility curve capturing natural uncertainty is obtained. This curve is called "reference fragility curve" since it is computed only with the probability distribution for the natural uncertainty, without considering epistemic uncertainty. Using only this reference fragility curve based on natural uncertainty could underestimate the actual failure probability due to effect of the epistemic uncertainty. This additional uncertainty can be captured in the adjustment proposed in Step 7.

- **Step 7.** First, groups of random variables are selected in the epistemic uncertainty distributions following the reliability method chosen for the epistemic uncertainty.

  Second, for each selected group of random variables, a new probability distribution is defined for the natural uncertainty, using as "new mean" these selected values and keeping the same standard deviations and probability distributions defined for the natural uncertainty. Afterwards, for each group of random variables, Step 6 is followed to estimate the corresponding fragility curve using the new probability distribution defined for natural uncertainty. Therefore, the differences between the fragility curves are the mean values of the probability distributions of the random variables used to compute them. As a result, the family of fragility curves obtained separately captures both the epistemic and natural uncertainty.

- **Step 8.** Check the outcomes and perform sensitivity analysis on any of the decisions previously taken. This last step is a crucial, as the engineer should never get lost in any mathematical approach that may not represent sound engineering judgment.

Finally, this family of fragility curves can be introduced into a complete and quantitative risk model to estimate failure probability and risk, analyzing the effect of reducing epistemic uncertainty in the risk results.

3.3.4 Case study: Fragility analysis of a concrete dam

In (Morales-Torres, Escuder-Bueno, Altarejos-García, et al. 2016), the procedure described in the previous section is applied to estimate a family of fragility curves for the sliding failure mode in a Spanish concrete dam. In this case, sliding along the concrete-foundation interface was considered for the central section. This section presents a triangular profile, as shown in Figure 11, with slopes of 0.05/0.76 (Upstream/Downstream). The dam crest level is at +911.4 meters and the foundation level is at +915.2 meters. The height of the cross section is 96.2 m above the foundation. The maximum operating level in the reservoir is +908.5 meters. The dam is located over a sub-vertical layer of quartzite of 70 m depth. These quartzites have cracked and split into fragments due to the effect of its fold. Vertical cracks are predominant due to the strong vertical folding.

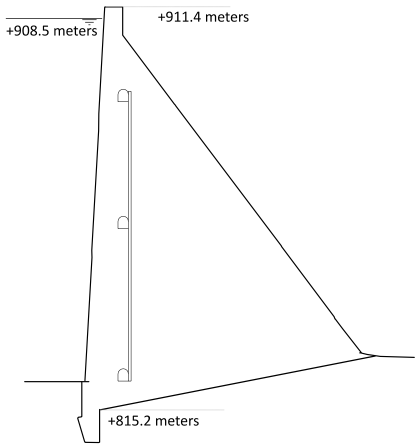

Figure 11. Cross section of the case study concrete dam. Source: (Morales-Torres, Escuder-Bueno, Serrano-Lombillo, et al. 2016).

According to previous analyses and studies, the engineers in charge of this dam had doubts about the safety of this dam for the sliding failure mode. For this reason, risk analysis was applied to estimate the current risk for the sliding failure mode in the dam and to propose potential risk reduction measures and/or measures to reduce epistemic uncertainty. Epistemic uncertainty was significant in this case, due to the lack of data about the original design and the foundation characteristics, so it was considered that separating both types of uncertainty was important for a proper risk-informed dam safety management.

The eight steps of this procedure were applied to obtain a family of fragility curves. In this case, since the uncertainty on the foundation resistance capacity is the main concern for the sliding failure mode, two independent random variables are considered within a Limit Equilibrium Model: friction angle and cohesion. For each random variable, two probabilistic distributions were estimated as shown in Table 1. The estimation of these probabilistic distributions by expert judgement was based on geotechnical in situ and laboratory tests, measurements procedures and temporal and spatial variations of results.

Random variable	Mean	St. Deviation	Maximum	Minimum	Type
			Natural uncertainty		
Friction angle (º)	50	5	65	35	Normal
Cohesion (MPa)	0.5	0.2	1.5	0.1	Log-Normal
			Epistemic uncertainty		
Mean friction angle (º)	50	2.5	60	40	Normal
Mean cohesion (MPa)	0.5	0.125	1	0.2	Log-Normal

Table 1. Probability distribution considered for the random variables to obtain the family of fragility curves. Source: (Morales-Torres, Escuder-Bueno, Altarejos-García, et al. 2016).

Therefore, a family of 1000 fragility curves was obtained for this dam. For instance, Figure 12 shows the family of fragility curves obtained for dam A. As explained, the spread of this family is an indicator of the influence of the epistemic uncertainty in the results.

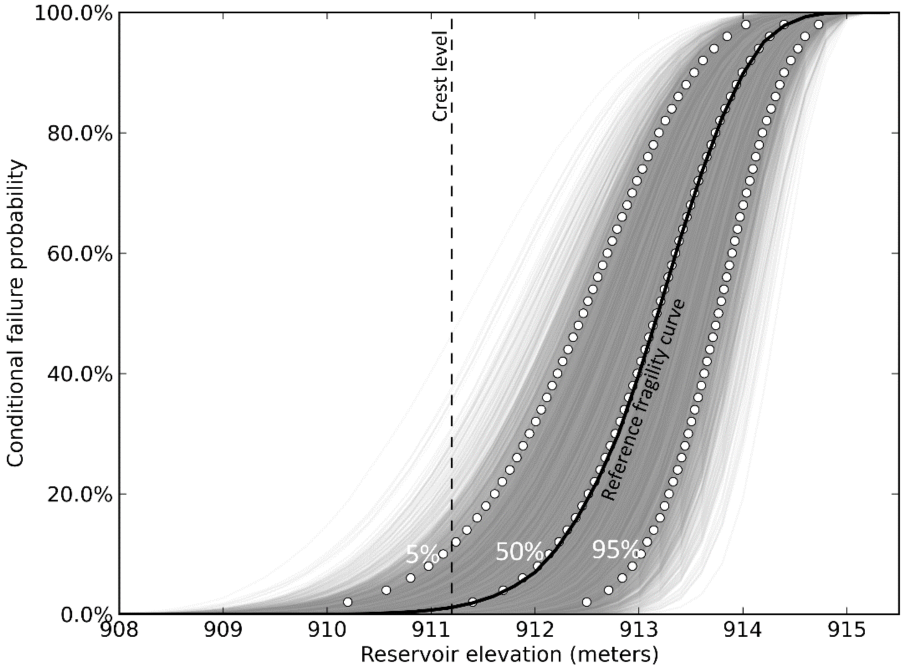

Figure 12. Family of fragility curves obtained for the case study dam. Source: (Morales-Torres, Escuder-Bueno, Serrano-Lombillo, et al. 2016).

One of the issues that has a higher influence in the results and the calculating times is the number of samples of the random variables chosen to estimate failure probability. In order to analyze the effect of this decision, the failure probability within the reference fragility curve was re-estimated depending on the number of samples for three different maximum water levels: +912, +913 and +914 meters Results are shown in Figure 13. As can be perceived in this figure, failure probability results were stable when the number of samples is higher than 1,000, so 10,000 samples was a good decision to achieve accurate results.

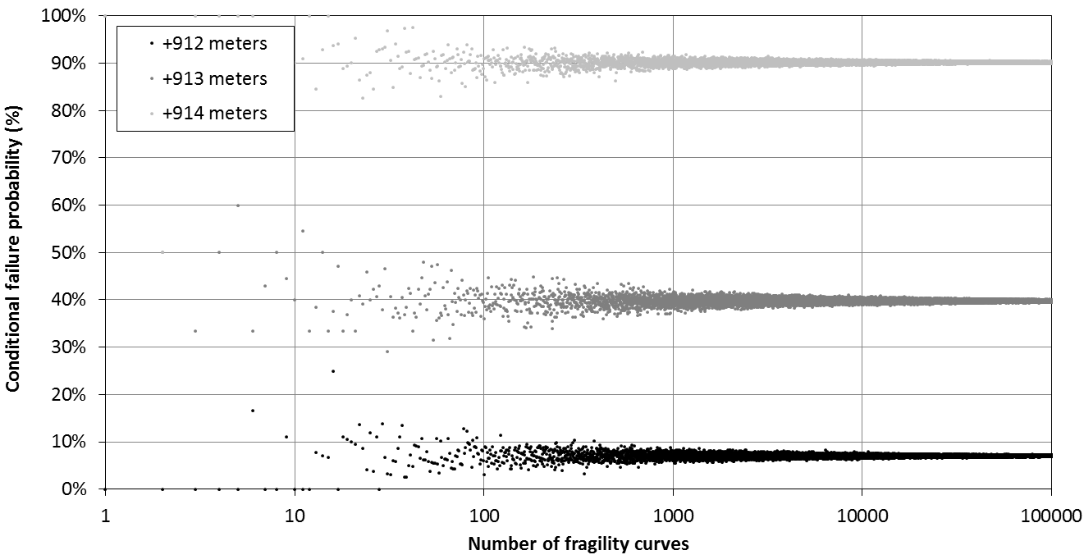

Figure 13. Failure probability for three reservoir elevations as a function of the number of samples used to compute them. Source: (Morales-Torres, Escuder-Bueno, Serrano-Lombillo, et al. 2016).

Finally, in (Morales-Torres, Escuder-Bueno, Serrano-Lombillo, et al. 2016) the family of fragility curves was introduced in a quantitative risk model elaborated for this dam in order to obtain a risk probability distribution for sliding failure. This risk model was elaborated using iPresas Calc software (iPresas 2014), which is based on event trees to compute failure probability and risk. Figure 14 shows the quantitative risk model structure. These risk models were used to compute risk for the current situation and for the 20 risk reduction measures analyzed.

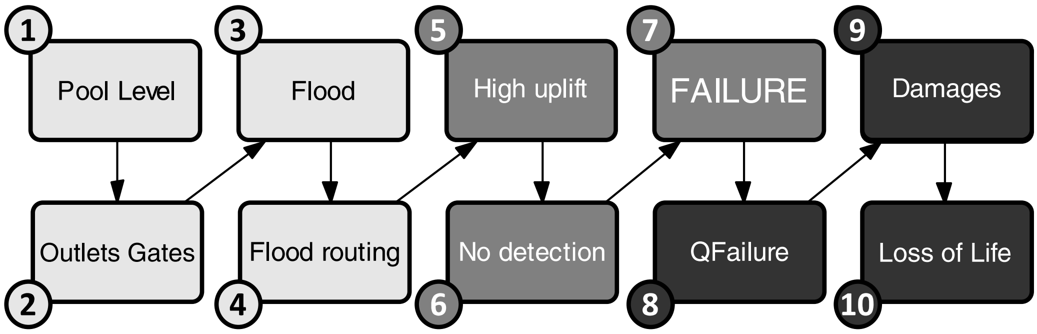

Figure 14. Risk model structure. Source: (Morales-Torres, Escuder-Bueno, Serrano-Lombillo, et al. 2016).

In the first four nodes (nodes 1-4), this model creates an event tree to compute the probability of different flood routing scenarios in the reservoir (for different flood events, different previous pool levels in the reservoir and different cases of spillway gates availability) in order to obtain an annual exceedance probability curve of the water pool level in the reservoir. Detailed procedures followed to compute this input data are explained in (A. Serrano-Lombillo, Fluixá-Sanmartín, and Espert-Canet 2012).

Nodes 5 and 6 are different for each dam and they estimate the probability of being in different uplift pressures hypothesis, following the sliding numerical model. Probabilities introduced in these nodes are based on foundation characteristics, available information about uplift pressures and existing capacity to detect and to avoid high uplift pressures.

Node 7 is used to incorporate the sliding fragility curves in order to relate the maximum water level reached in the reservoir in each flood event with the conditional failure probability. The failure probability of each branch of the event tree is computed multiplying the probabilities of all the nodes. Consequently, when the probabilities of all the branches of this event tree are added, the dam failure probability due to sliding is obtained.

Nodes 8-10 are used to compute consequences in order to estimate risk, following equation 1. Node 8 is used to introduce a relation between the water pool level and the peak failure discharge. This relation was previously computed using hydraulic models of the dam breach. Finally, Nodes 9 and 10 introduce the relation between failure discharge and loss of life and economic consequences due to failure. These consequences for different discharges were also computed using a hydraulic model of the dam break flood. Detailed procedures followed to derive consequences input data are explained in (A. Serrano-Lombillo, Morales-Torres, and García-Kabbabe 2012).

For each curve of the family of fragility curves shown in Figure 12, this risk model was used to compute failure probability, economic risk and societal risk. Therefore, societal risk results were sorted to obtain the societal risk probability distribution shown in Figure 15. The variation of this risk distribution indicates the degree of deviation of risk results due to epistemic uncertainty.

In conclusion, a procedure is presented for fragility analysis of sliding failure of concrete gravity dams make use of reliability methods and formally distinguishing two main sources of uncertainty, natural and epistemic. The suggested eight step framework focuses on the options and decisions that an analyst has to face, trying not to hide crude real world decisions behind the elegance and accuracy of mathematics.

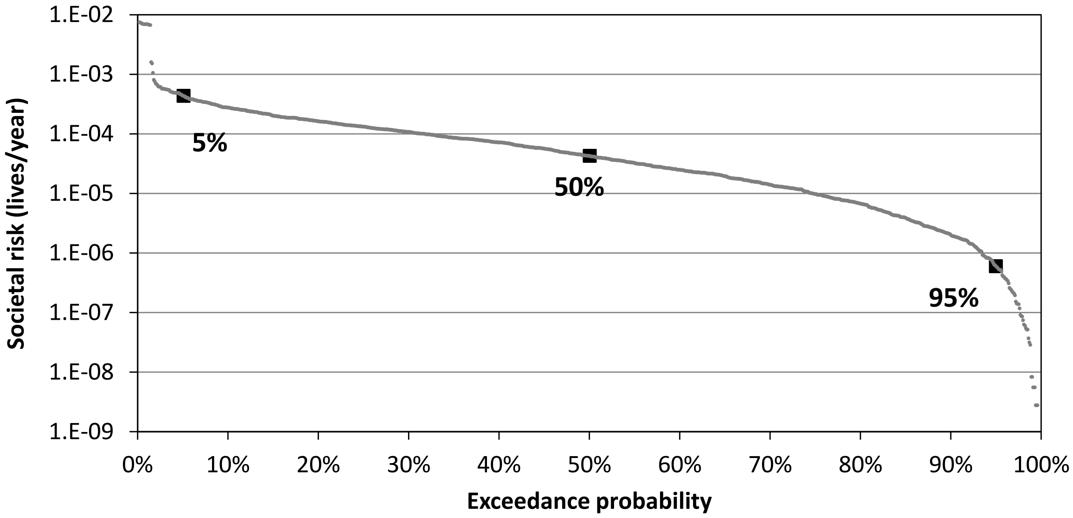

Figure 15. Societal risk probability distributions obtained for the case study dam. Adapted from: (Morales-Torres, Escuder-Bueno, Serrano-Lombillo, et al. 2016).

This procedure is focused on the system response term of the risk equation, but, as explained previously, distinguishing natural and epistemic uncertainty is also necessary when loads and consequences are addressed.

The impact of the epistemic uncertainty span on the overall risk picture appears as valuable information regarding the design and urgency of the actions needed to reduce the gap in knowledge and so to improve the safety of the dam.

3.4 Measuring the effect of epistemic uncertainty in dam safety decision making

3.4.1 Risk reduction measures vs. epistemic uncertainty reduction measures

In dam safety management, two types of investments can be analyzed: risk reduction measures (higher outlets capacity, freeboard requirements…) and uncertainty reduction measures (geotechnical tests, dam computational models…).

These two types of measures have a different impact on a risk probability distribution obtained by a second-order probability risk assessment. Risk reduction measures move the probability distribution downwards, while measures to reduce epistemic uncertainty produce a less steep risk distribution, as shown in Figure 16.

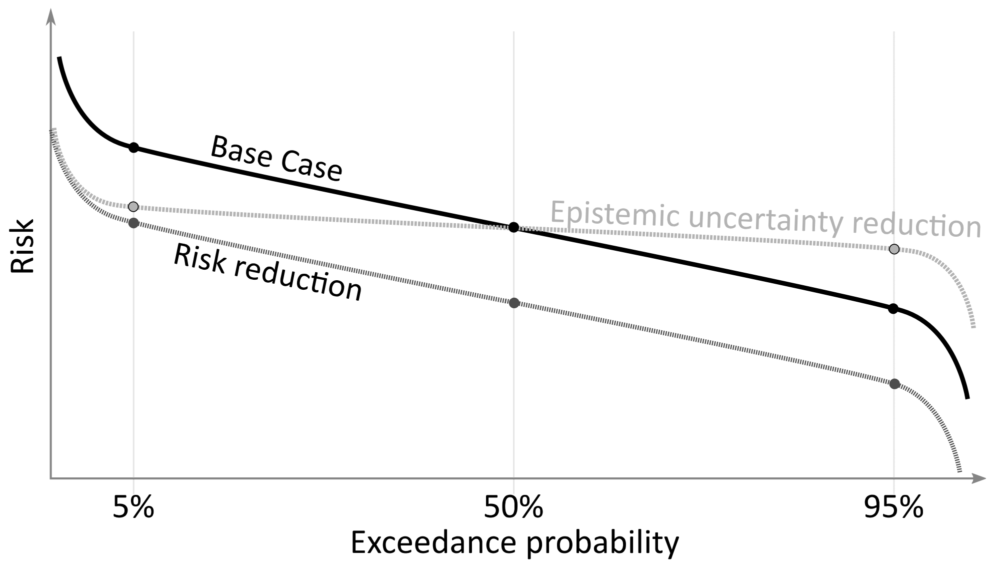

Figure 16. Example of the effect in a risk distribution of a risk reduction measure and an epistemic uncertainty reduction measure. Source: (Morales-Torres, Escuder-Bueno, Serrano-Lombillo, et al. 2016).

The procedure presented in Section 3.2 to inform dam safety with risk reduction indicators is focused on average risk results from first-order probabilistic risk analysis. For this reason, it is used to prioritize risk reduction measures but it does not analyze the effect of epistemic uncertainty. However, this type of uncertainty can influence decision making and prioritization sequences. For instance, in high epistemic uncertainty situations, the decisions made can change depending on the values considered within the epistemic uncertainty distributions.

As explained in Section 3.3.1, in a second-order probabilistic risk analysis a high number of risk results are obtained instead of a single risk value. The spread of these results indicates the existing epistemic uncertainty. Hence, a high number of risk results are obtained for the base case and for each risk reduction measure analyzed.

When these results are combined with the calculation of prioritization sequences explained in Section 3.2, a high number of sequences are obtained for each risk reduction indicator, instead of a single sequence for the average values. The differences between these high number of sequences indicate how epistemic uncertainty influences decision making. In a case where epistemic uncertainty is not influential, the order of the analyzed measures in all the sequences will be the same, while in a case with a high influence of epistemic uncertainty, there will be higher differences in the order of measures within the sequences. This is the key of dealing with epistemic uncertainty within dam safety management: analyzing how it can change the decisions made and when it is recommended to invest in reducing this type of uncertainty.

3.4.2 Indexes of Coincidence to analyze epistemic uncertainty in dam safety decision making

In order to measure analyze the effect of epistemic uncertainty in measures prioritization, two different indexes were developed and proposed in (Morales-Torres, Escuder-Bueno, Serrano-Lombillo, et al. 2016). These metrics are based on the difference in the order of measures between each sequence obtained with the results of a second-order probabilistic risk analysis and the reference sequence obtained with the average values from first-order risk analysis. The two indexes developed were:

- **Index of Coincidence (IC):** It quantifies the difference in the order of measures between two sequences. It is computed with the following equation:

$$IC = \left(\sum_{i=1}^{N} 1 - {|pr_i - p_i|}\Big/{(\max(pr_i - 1, N - pr_i))}\right)\Big/N \qquad \textit{Eq. 6}$$

  Where N is the number of measures in the sequences compared, pr_i is the position of the measure i in the reference sequence and p_i is the position of the measure i in the sequence compared with the reference sequence.

Figure 17 graphically shows how this indicator is computed in an example. For each step of the measure, it is computed with the division of the difference in the position of a sequence in the two itineraries (A in this figure) and the maximum difference in the position that there could be (B in this figure).

- **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. This adjustment factor varies from 2 for the first step of the measure to 0 for the last step. It can be computed with the following equation:

$$AIC = \left(\sum_{i=1}^{N} IC_i \cdot \frac{2\cdot(N_i - p_i)}{N-1}\right) \Big/ N \qquad \text{Eq. 7}$$

Where IC_i is the partial Index of Coincidence for measure i in the sequence, obtained with Equation 6.

Table 2 illustrates how these two indexes are calculated for the example shown in Figure 17. In this table, AIC_i are the partial Adjusted Index of Coincidence for each step of the sequence, obtained with equation 6. The name of Index of Coincidence was chosen based on the Index of Coincidence used in cryptography to analyze the similarity between two texts (Friedman 1987).

Thus, these indexes 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. Hence, a high number of Indexes of Coincidence are obtained, one for each sequence. The average Index of Coincidence of all these sequences 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.

With this approach, results of first-order probabilistic risk analysis can be used to define the reference prioritization sequence for risk reduction measures, while average Index of Coincidence indicate the influence of epistemic uncertainty and the need for uncertainty reduction measures.

Although the average Index of Coincidence can be computed when epistemic uncertainty is introduced in the three parts of the risk equation, as explained in

Section 3.3.2, they may be more useful when they are computed after introducing epistemic uncertainty in just one part of the input data.

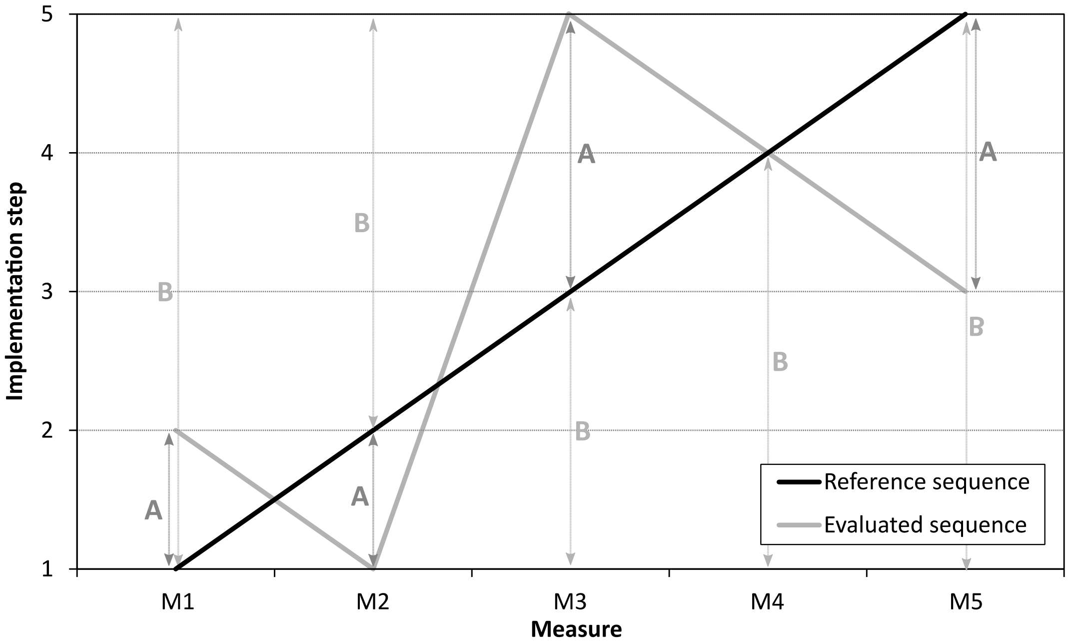

Figure 17. Graphical representation of Index of Coincidence to compare two prioritization sequences. Source: (Morales-Torres, Escuder-Bueno, Serrano-Lombillo, et al. 2016).

Measure	p_i	pr_i	Difference between itineraries (A)	Maximum possible difference (B)	IC_i	Adjustment factor	AIC_i
M1	2	1	1	4	75%	2	150%
M2	1	2	1	3	67%	1.5	100%
M3	3	3	2	2	0%	1	0%
M4	4	4	0	3	100%	0.5	50%
M5	5	5	2	4	50%	0	0%
Index of Coincidence					**58%**		
Adjusted Index of Coincidence							**60%**

Table 2: Example of calculation of Indexes of Coincidence to compare two prioritization sequences with five measures. Source: (Morales-Torres, Escuder-Bueno, Serrano-Lombillo, et al. 2016).

With this purpose, the main sources of epistemic uncertainty in the risk model can be identified and their average Indexes of Coincidence can be independently computed to identify the sources of epistemic uncertainty that have a higher influence in the decision making. According to (Morales-Torres, Escuder-Bueno, Serrano-Lombillo, et al. 2016), Table 3 shows reference values of average Indexes of Coincidence and what they could indicate when they are computed for a single source of uncertainty in the risk model.

Average Index of Coincidence value	Degree of influence of this source of epistemic uncertainty in measures prioritization
> 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

Table 3: Indicative meaning of average Index of Coincidence when computed for a single source of epistemic uncertainty.

Finally, Indexes of Coincidence indicate the need for epistemic uncertainty reduction measures, so they are very useful for risk-informed dam safety management. In this sense, the effect of epistemic uncertainty reduction measures in the probability distributions introduced in the risk model can be estimated and Indexes of Coincidence can be recomputed. Expected increments in average Indexes of Coincidence of more than 5% indicate effective uncertainty reduction measures, especially when Indexes of Coincidence are lower than 85%.

3.4.3 Case study: Risk management in 4 gravity dams

The approach introduced in (Morales-Torres, Escuder-Bueno, Serrano-Lombillo, et al. 2016) was applied to inform safety management in four existing concrete gravity dams in Spain. Main characteristics of these dams are summarized in Table 4. As can be observed, it is a heterogeneous group of concrete gravity dams in size and age. Dam A in this group is the dam used for the case study of Section 3.3.4.

Dam	Height (m)	Reservoir volume (hm^3)	Upstream slope	Downstream slope	Construction year
A	91.2	308	0.05	0.76	1956
B	31.5	0.3	0.15	0.7	1991
C	58	496	0	0.767	1960
D	59.5	24.4	0.05	0.76	1954

Table 4: Main characteristics of case study dams.

The starting point for this case study was the risk models elaborated within a first-order probabilistic risk analysis performed on each dam. The analysis made was focused on the potential sliding of these dams and the epistemic uncertainty about the foundation resistant capacity. Hence, the analysis introduced in this case study was focused on this source of epistemic uncertainty within the risk model and how it can influence decision making.

Sliding safety management in these dams deals with the prioritization of potential risk reduction measures and/or investing in reducing uncertainty about the foundation. A total number of 20 potential risk reduction measures (summarized in Table 5) were analyzed in the four analyzed dams. These structural and non-structural measures came from a list of actions already planned by the operators to improve dam safety along with the needs revealed by the results of the risk analysis process.

Dam	Risk reduction measures	Dam	Risk reduction measures
A	1. Improve spillway gates reliability	C	1. Improve foundation conditions
	2. Emergency Action Plan		2. Emergency Action Plan
	3. Improve reliability of intermediate outlet gates		3. Improve reliability of spillway gates
	4. Injections to improve foundation conditions		4. Improve monitoring system
	5. New piezometers to measure uplift pressures		5. New freeboard requirements
B	1. Improve drainage system	D	1. Improve dam access
	2. Emergency Action Plan		2. Emergency Action Plan
	3. Improve reliability of bottom outlet gates		3. Improve drainage system
	4. Increase spillway capacity		4. Improve monitoring system
	5. Improve monitoring system		5. Remote control for spillway gates

Table 5: Analyzed risk reduction measures analyzed for case study dams.

Firstly, following the procedure detailed in Section 3.3.3, a family of 1000 fragility curves were obtained for each dam. The spread of this family is an indicator of the influence of the epistemic uncertainty in the results.

Secondly, the family of fragility curves were introduced in the quantitative risk model elaborated for each dam in order to obtain a risk probability distribution for sliding failure, following the same procedure that is explained in Section 3.3.4. As explained, these risk models were elaborated using iPresas Calc software (iPresas 2014) and the four risk models have a similar structure.

For each curve of the family of fragility curves of each dam, these risk models were used to compute failure probability, economic risk and societal risk. For each dam, societal risk results were sorted to obtain the societal risk probability distribution shown in Figure 18. As can be observed in these graphs, societal risks are higher for Dam B and Dam C, while risk variations due to epistemic uncertainty are higher for Dam A and Dam D.

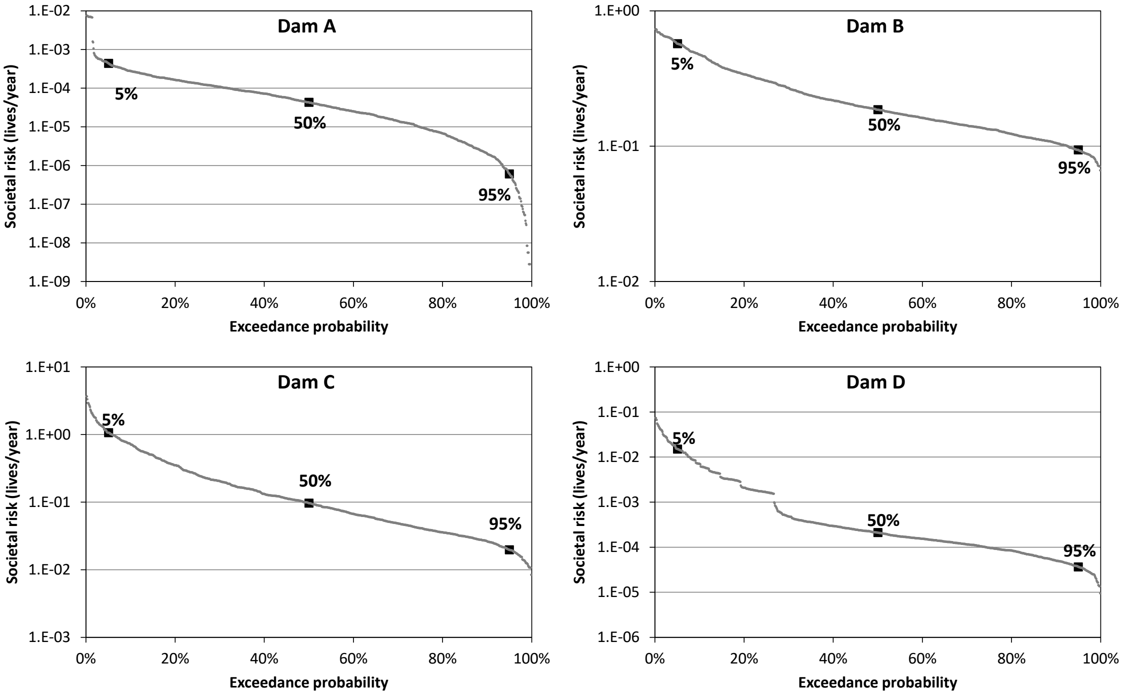

Figure 18. Societal risk probability distributions obtained for the four dams. Source: (Morales-Torres, Escuder-Bueno, Serrano-Lombillo, et al. 2016).

Thirdly, once these risk distributions were obtained, Indexes of Coincidence proposed and described in Section 3.4.2 were computed to solve the key question proposed: Is epistemic uncertainty influencing decision making?

With this purpose, the 20 risk reduction measures analyzed were prioritized following the procedure explained in (Morales-Torres, Serrano-Lombillo, et al. 2016), using the EWACSLS indicator (Armando Serrano-Lombillo et al. 2016), combining equity and efficiency principles.

A reference implementation sequence of measures was obtained with the risk results obtained with the reference fragility curve in each dam. Next, 1000 implementation sequences were obtained combining the 1000 fragility curves and their risk results obtained for each dam. These 1000 sequences were compared with the reference sequence to obtain the average Indexes of Coincidence shown in Table 6. As can be observed in this table, these indexes were computed after prioritizing measures for each dam independently and prioritizing the 20 measures together. Figure 19 shows the variation graphs of all sequences obtained for the prioritization of the 20 measures together.

Dam	Index of Coincidence	Adjusted Index of Coincidence
A	99.35%	99.29%
B	79.86%	69.55%
C	87.42%	86.97%
D	94.11%	90.77%
All the dams	86.95%	86.60%

Table 6: Indexes of Coincidence obtained for the case study. Source: (Morales-Torres, Escuder-Bueno, Serrano-Lombillo, et al. 2016).

As can be observed, Indexes 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, Indexes of Coincidence for Dam A are close to 100%, which showed that epistemic uncertainty has low influence on decision making. Indexes of Coincidence of Dams C and D indicate a medium influence of epistemic uncertainty on results.

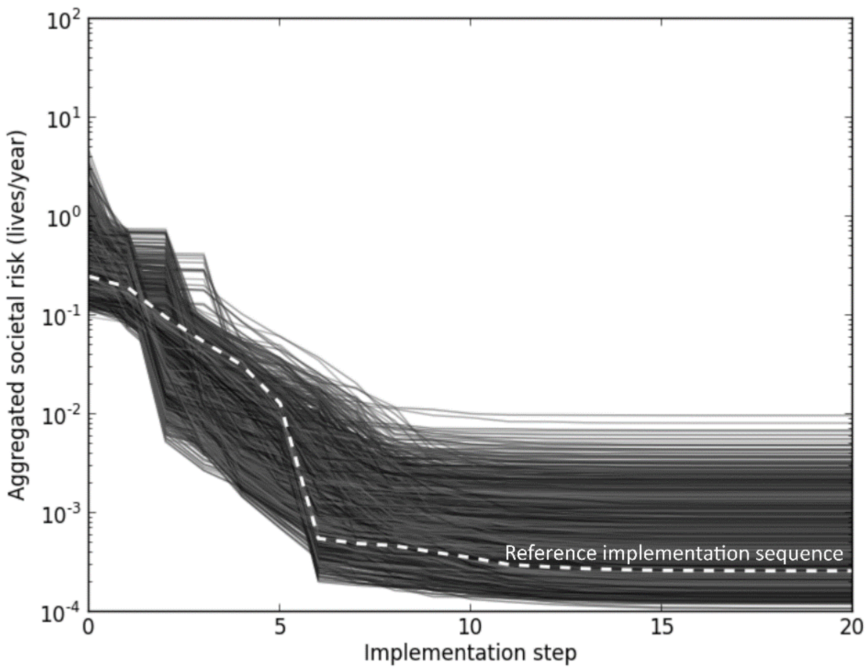

Figure 19. Variation graphs of the 1000 sequences obtained for the prioritization of the 20 measures together. Y axis represents aggregated societal risk of the four dams. Source: (Morales-Torres, Escuder-Bueno, Serrano-Lombillo, et al. 2016).

Finally, the potential effect of epistemic uncertainty reduction measures for the foundation resistance capacity, like geotechnical tests and detailed surveys, was analyzed. With this purpose, the previous computations were repeated but reducing by half the standard deviation of the epistemic uncertainty probabilistic distributions. In this case, the risk probability distributions shown in are obtained. It is obtained that reducing epistemic uncertainty has a direct effect in the steepness of probability distributions.

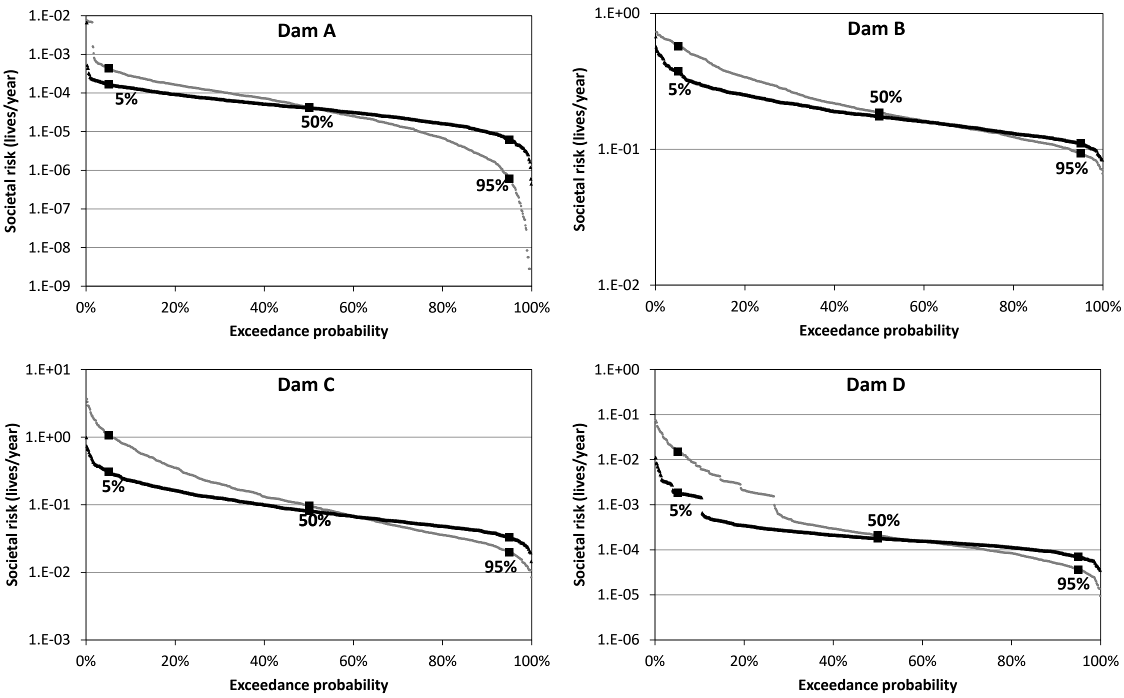

Figure 20. Societal risk probability distributions for all dams: base case (grey line) and after reducing epistemic uncertainty (black line). Source: (Morales-Torres, Escuder-Bueno, Serrano-Lombillo, et al. 2016).

Next, the same procedure was followed to obtain 1000 sequences of risk reduction measures for each dam individually and combining them. The itineraries for the combined case are shown in Figure 21. As expected, the spread of the itineraries is lower, although it does not mean that the measures are implemented in a different order that in Figure 19.

Thus, Indexes of Coincidence were recomputed for these cases as shown in Table 7. As can be observed the effect of reducing epistemic uncertainty in each dam was independently analyzed in the individual sequences of each dam and in the sequences obtained combining the four dams.

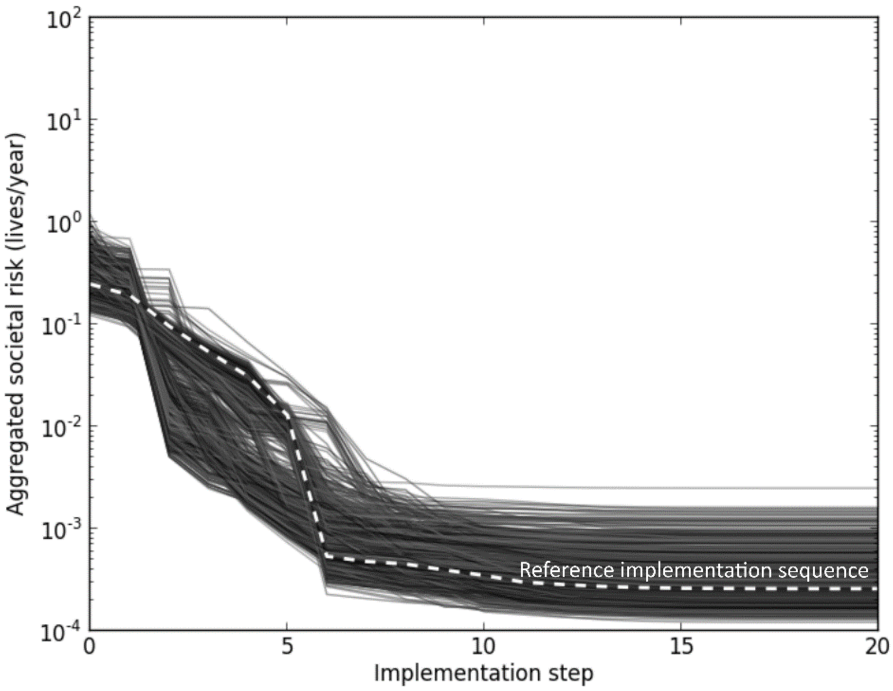

Figure 21. Variation graphs of the 1000 sequences obtained for the prioritization of the 20 measures after reducing epistemic uncertainty. Source: (Morales-Torres, Escuder-Bueno, Serrano-Lombillo, et al. 2016).

	Base case		**Epistemic uncertainty reduction**		**Difference**	
Epistemic uncertainty reduction	**Index of Coincidence**	**Adjusted Index of Coincidence**	**Index of Coincidence**	**Adjusted Index of Coincidence**	**Index of Coincidence**	**Adjusted Index of Coincidence**
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%

Table 7: Indexes of Coincidence: base case and after reducing epistemic uncertainty. Source: (Morales-Torres, Escuder-Bueno, Serrano-Lombillo, et al. 2016).

Results show that reducing epistemic uncertainty in Dam C and Dam D would have a higher influence in the decision making process for the whole system of dams. In contrast, the effect of reducing epistemic uncertainty in Dam A is lower. Epistemic uncertainty reduction in Dam B has a high effect in the sequences obtained for this dam individually but its effect in the management of the four dams together is more limited. Hence, epistemic reduction actions are recommended when this dam is individually managed, but from the combined management point of view, these actions would be more recommended in Dams C and D. Therefore, these Indexes of Coincidence are useful to identify how epistemic uncertainty is influencing decision making in each dam.

If the results of reducing globally epistemic uncertainty for the four dams are analyzed, it can be concluded that these actions could be useful to support a better risk-informed decision making, since they provide an increment of Indexes of Coincidence by 4%.

In conclusion, the metrics proposed have significant advantages to inform dam safety governance, since they allow measuring the effect of epistemic uncertainty in decision making. Hence, they help to identify needs for reducing gaps in dam knowledge, giving value to measures that do not have a direct effect on average risk results.

This case study is focused on one source of uncertainty within the risk model: foundation resistant capacity. This approach of analyzing each source of epistemic uncertainty separately is more recommended since it allows to identify what type of epistemic reduction actions are more effective. In any case, if epistemic uncertainty is included in all the nodes of the model as explained in Section 3.3.2, Indexes of Coincidence can also be obtained although they will be lower, since the effect of different sources of epistemic uncertainty is combined.

Hence, the introduced case study is focused on epistemic uncertainties in the second term of the risk equation: the system response, but Indexes of Coincidence can also be used to analyze the effect of epistemic uncertainty in the other terms: loads probability and consequences.

Even though the introduced metrics are based on risk prioritization sequences obtained with risk reduction indicators, they could also be used to compare the influence of epistemic uncertainty in other types of measures prioritization sequences.

Although Indexes of Coincidence were developed within the dam safety management field, they could be also applied to analyze the effect of epistemic uncertainty in other fields. The concepts behind these indexes are equally appropriate for other critical infrastructures, since addressing the effect of epistemic uncertainty is very important for an integrated risk management.

4 Conclusions

4.1 Final conclusions

This thesis provides procedures and metrics to ensure that quantitative risk results are useful and effective to inform dam safety governance. The main conclusions obtained are:

- Risk reduction indicators are a useful tool to manage quantitative risk results in complex systems with many alternatives of investment. These indicators can be used to create prioritization sequences of risk reduction measures according to two risk reduction principles: equity and efficiency.
- As demonstrated in the portfolio case study, prioritization of different structural and non-structural measures in a consistent and justifiable way can be accomplished by using the results offered by risk models and risk reduction indicators, even in heterogeneous groups of dams.
- The EWACSLS indicator has proved to be very useful to obtain prioritization sequences of measures since it enables to obtain a prioritized sequence that balances efficiency and equity while offering good results for both principles. These advantages make EWACSLS an excellent indicator for real-world use in risk management decision making which smoothly blends efficiency and equity considerations.
- In practice, each critical infrastructure operator will choose the principles and tolerability limits that reflect its values and objectives more adequately. Besides, management of critical infrastructure safety actions can incorporate many factors of administrative, societal and economic order, difficult to quantify and that might condition decision-making. Within this context, measure implementation sequences based on risk results provide valuable information to decision-making and in some cases can be an input to a more global multi-criteria analysis.
- Dams are located in natural and heterogeneous environment that cannot be controlled. For this reason, unlikely to other industries, dam safety governance deals with higher natural and epistemic uncertainties since it is directly related with the nature behavior. For this reason, epistemic uncertainty can have a higher effect on decision making, which remarks the importance of dealing with it. Although this is not the most common approach in the dam safety field, the distinction between both types of uncertainty, as proposed in this thesis, takes added importance for a proper dam safety management.

- The Indexes of Coincidence proposed in this research have significant advantages to inform dam safety governance, since they allow measuring the effect of epistemic uncertainty in decision making. Hence, they help to identify needs for reducing gaps in dam knowledge, giving value to measures that do not have a direct effect on average risk results.
- These metrics allow considering the convenience of conducting additional uncertainty reduction actions, like site tests, surveys or more detailed analysis, prior to investing in risk reduction measures.
- Finally, it should be remarked that the intent of this thesis is dealing with uncertainty, more than fighting against uncertainty, which is identified as one of the main elements of smart governance.
- In fact, concerns on dealing with uncertainty is one of the main identified barriers for risk governance in large dams, which this thesis helps to overcome.
- In addition, having more rational and structured quantitative information to support dam safety management, able to capture different values depending on the context (country, regulatory framework, liability, business culture, etc.) will be in the benefit of any dam owner or decision maker.

4.2 Further research proposals

According to the professional experience of the author and the main findings of this thesis, the following research lines are proposed in order to improve risk-informed dam safety management:

- A future research line is finding a consistent manner to evaluate time issues in the prioritization sequences of measures, such as the expected time to complete a corrective action and the balance between short term and long term actions.
- The procedures and case studies of this thesis are focused on epistemic uncertainties in the second term of the risk equation: the system response, but future researches could also be focused on the probability of loadings or consequences terms, analyzing the effect of uncertainty reduction measures in this data. Therefore, uncertainties could be propagated in the risk equation through convolution.
- In addition, following the structure developed for the sliding failure, a procedure could be developed to separate epistemic and natural uncertainty in the internal erosion failure of embankments, since this failure mode is usually related with significant epistemic uncertainties.

- The combined effect of risk reduction measures that also help to reduce epistemic uncertainty could be analyzed through a risk reduction indicator that include epistemic uncertainty considerations. For example, improvements in the surveillance and monitoring system, since they help to detect the failure modes occurrence and increase the knowledge about the dam behavior.
- In future researches, new metrics could be developed combining the changes of uncertainty reduction measures in the Indexes of Coincidence and the costs of these measures. These metrics could be useful to compare uncertainty reduction measures with risk reduction indicators obtained for risk reduction measures.

Finally, though the methods and metrics proposed has been proved for large dams, it can be easily envisioned how it would be possible to tailor it for different types of civil infrastructures where best practices already include risk identification, calculation, evaluation, assessment and management (i.e. transportation, energy production, etc.).

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Annex 1

The Suitability of Risk Reduction Indicators to Inform Dam Safety Management

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PAPER

The suitability of risk reduction indicators to inform dam safety management

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Risk analysis can provide very suitable and useful information to manage the safety of critical civil infrastructures. Indeed, results of quantitative risk models can be used to inform prioritization of safety investments on infrastructures' assets and portfolios. In order to inform this prioritization, a series of risk reduction indicators can be used. This paper reviews existing indicators for dam safety, tracks how equity and efficiency principles are captured, propose additional indicators and provides insights on how tolerability guidelines and benefit-cost analysis can also play a role in decision-making. All reviewed, analyzed and/or combined indicators are later applied in a case study, a portfolio of 27 dams where 93 structural and non-structural investments are prioritized. The case study shows that prioritization sequences based on risk model results provide suitable and useful information, acknowledging that other concerns may be conditioning decision-making processes. With the results of the case study, a full comparison between all studied risk reduction indicators is made, and three indexes are calculated for all of them to measure how close they are to a theoretical best.

Keywords: Dam Safety; Decision making; Risk management; Risk & probability analysis; Quantitative analysis; Risk reduction indicators; Risk reduction principles; Equity & efficiency

1. Introduction

Critical infrastructures are those whose failure or destruction would entail serious consequences for community safety, from economic damage to even loss of life. Some examples include electrical power systems, gas and oil storage and transportation, water supply systems, transportation, finance and banking, emergency and government entities (Clinton (1996)). In the hydraulic infrastructures field, one of the most critical infrastructures are large dams and protective dikes and levees.

There is always a probability associated with critical infrastructure failure, even if it might be very low. Thus, since there are always possibilities for adverse consequences to happen there is always an associated risk. Risk Analysis is a useful methodology to characterize this risk and establish priorities in critical infrastructure safety management since it allows the integration of all existing information on threats, vulnerability and consequences (Moteff (2005)). It enables robust and defendable safety decisions (Bowles (2001)) and the comparison of risk in all kinds of critical infrastructures (Ayyub et al. (2007);Ellingwood (2005)).

A full Quantitative Risk Analysis (QRA) provides a lot of information and many insights into the safety of a critical infrastructure. This detailed information can be used to better understand safety issues, propose risk reduction measures and estimate their impacts. On the other hand, when

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dealing with a large portfolio of infrastructures and risk reduction measures, some kind of summary indicator or indicators can be used in order to make manageable comparisons possible.

This paper reviews several risk reduction indicators and shows their utility to manage quantitative risk results in complex systems with many alternatives of investment. These indicators can be used to create prioritization sequences of risk reduction measures according to two risk reduction principles: equity and efficiency. This prioritization procedure is contextualized within the Tolerability of Risk (TOR) framework, which was set out by UK's HSE (2001) for risk evaluation and management and has been widely used in dam safety (ANCOLD (2003); SPANCOLD (2012); USACE (2014); USBR (2011a)). In order to show the utility of this procedure, it was applied to the safety management of a group of 27 dams and different mitigation measures sequences were obtained according to efficiency and equity principles.

This paper does not discuss the way in which QRA are carried out but rather takes their results as its starting point to obtain these risk indicators. However, it is important to note that a single indicator can never convey all the information that a full QRA provides, therefore, one must refer back to the full QRA when looking for specific information. Moreover, recommendations based on this type of indicators should not be taken as prescriptions, since there is always the possibility that an important issue may not be adequately reflected in a summary indicator.

It should be mentioned that risk informed decision-making is very complex, and not only technical aspects are important, but political, psychological and societal considerations also play a significant role (Jonkman (2003)) and it may not be possible to include them in a quantitative risk analysis. In such a broad and interconnected context, multi criteria analysis (Figueira et al. (2005); Keeney & Raiffa (1993); Saaty (1988); Kabir et al. (2014)) is universally seen and used as a conceptual and analytical tool to make all kind of decisions related, among many others, to investments.

2. Risk informed safety management based on equity and efficiency principles

2.1. *Risk estimation*

In risk analysis applied to critical infrastructures, risk can be defined as the combination of three concepts: what can happen (critical infrastructure failure), how likely it is to happen (failure probability), and what its consequences are (failure consequences, including but not restricted to economic damages and loss of life) (Kaplan (1997)). Based on this definition, risk can be quantified in several ways, and sometimes several conflicting definitions are used for similar concepts. Those used in the present paper are defined below:

- **Individual risk (R_I):** Several subtly different definitions of individual risk are in use. One of them is the probability that an average unprotected person, permanently present at a certain location is killed due to an accident resulting from a hazardous activity (Bottelberghs (2000); Jonkman (2011)). This definition yields an individual risk *distribution* which varies spatially. Another definition is the probability that at least one person dies as a result of the critical infrastructure's failure (SPANCOLD (2012)). This definition has the advantage of yielding a single number. Its units are 1/year and it can be formulated as:

$$R_I = \int_e p(e) \cdot p(f|e) \cdot p(d \geq 1|f,e) \cdot de \qquad (1)$$

  Where the integral is defined over all events e under study, $p(e)$ is the probability of an event, $p(f|e)$ is the probability of failure due to event e and $p(d \geq 1|f,e)$ is the probability that at least one person dies due to this failure. If in an specific application it can be assumed that all failures would produce at least one fatality, that is, if $p(d \geq 1|f,e) = 1$, then individual risk is equivalent to failure probability.
- **Societal risk (R_S):** It is obtained by combining failure probabilities and the harmful con-

sequences suffered by the population as a result of that failure (Jones (1985)). These consequences are generally expressed in terms of loss of life. Societal risk is commonly represented through FN curves that show the relation between loss of life and exceedance probability. The area under these curves is equivalent to the expected number of deaths per year (Vrijling & van Gelder (1997)). This number can be used to represent societal risk with a single value, and it is also known as estimated annualized loss of life (Bowles (2004)). Mathematically, it is obtained through the following formula:

$$R_S = \int_e p(e) \cdot p(f|e) \cdot c_S(f,e) \cdot de \quad (2)$$

Where $c_S(f,e)$ is the loss of life due to each failure f and event e.

- **Economic risk (R_E):** Economic risk is obtained by combining failure probability and the economic consequences of that failure (Jonkman (2003)). These consequences are expressed in monetary units. Similarly to societal risk, economic risk can be represented with FD curves or with the expected annualized economic damage (Bowles (2004)), obtained through the following formula:

$$R_E = \int_e p(e) \cdot p(f|e) \cdot c_E(f,e) \cdot de \quad (3)$$

Where $c_E(f,e)$ are the economic consequences produced as a result of each failure f and event e.

For risk calculation, the use of risk models (USBR (2011b)) that define the variables affecting infrastructure safety and the relations between them is common. Once a risk model is set up, it is then possible to estimate failure probability, consequences and risks.

2.2. *Risk evaluation and management*

Once the risk is calculated it must be evaluated in order to determine the need of implementing mitigation measures. Risk evaluation is the stage where judgments and values are introduced into the decision-making (whether explicitly or implicitly) by including the consideration of the importance of the estimated risks (ICOLD (2005)). The procedure described in this paper is based on the concepts of the Tolerability of Risk (TOR) framework HSE (2001) for risk evaluation and management. Therefore, these core concepts and principles regarding risk, tolerability of risk and risk management are not discussed in this paper, where such principles are taken in the same way as the above mentioned references do. This framework is widely used worldwide for risk informed dam safety management (ANCOLD (2003); SPANCOLD (2012); USACE (2014); USBR (2011a)).

Within this framework, risk evaluation is based on the concepts of unacceptable risk, tolerable risk and broadly tolerable risk (HSE (2001)). From these concepts, several international organizations have developed risk tolerability recommendations to evaluate whether a risk is tolerable or not. Several examples for hydraulic infrastructures can be found (Bottelberghs (2000); NSWDSC (2006); USACE (2014); USBR (2011a); Vrijling & van Gelder (1995)) for individual and societal risk.

Finally, the key part of the risk analysis process is decision-making for risk management. Decisions are made after considering possible alternatives and analyzing their effect on infrastructure risk. Generally, two principles are recommended to guide this decision-making process (HSE (2001); ICOLD (2005); USACE (2014)):

- **Equity:** In the context of critical infrastructure safety management, this principle arises from the premise that all individuals have unconditional rights to certain levels of protection (Le Guen (2010)). Among the different risk components which have been presented (see definitions in section 2.1), individual risk (the probability that at least one person dies as a result of the critical infrastructure's failure) is the most related to this concept.

Hence, individual risk tolerability recommendations seeking a certain level of protection for every individual of the population are related to the principle of equity. According to HSE (2001), the application of this principle should prevail when individual risk is above the recommended value of tolerability. There are numerous recommendations to establish this value, varying according to the activity or industry under study. Some examples can be seen in the Dutch regulations (Vrijling & van Gelder (1995)) and in the guidelines by USACE (2014).

- **Efficiency:** This principle arises from the fact that society possesses limited resources which must be spent in the most efficient way. When considering several risk reduction measures, the one producing a higher risk reduction at a lower cost (the one that optimizes expenditure) should generally be chosen first. This is usually the prevailing principle when risk is tolerable (HSE (2001)). In this paper we suggest a distinction between two types of efficiency, depending on the targeted risk:
  - **Societal efficiency:** When the target risk to be reduced is societal risk.
  - **Economic efficiency:** When what is analyzed is economic risk reduction, that is, the searched strategy is the most advantageous from an economic point of view. According to some authors (Bowles (2001)), this type of efficiency should only prevail when the infrastructure complies with tolerability recommendations.

  The efficiency principle is followed when a Benefit-Cost Analysis is made for risk informed decision-making. This approach addresses societal and economic efficiency by aggregating societal and economic risk (Baecher et al. (1980); HSE (2001); NRC (2014)). For this purpose, loss of life is given an economic value (known as Value Per Fatality or VPF), estimated from the population's willingness to pay to acquire a certain level of protection.

In summary, two different principles are generally used to guide decision-making within the tolerability framework: equity and efficiency. This can result in contradictions since what can be an optimal measure from the equity point of view may not be so from the efficiency point of view and vice versa. Decisions based on tolerability criteria and equity could lead to economically inefficient investments but a pure efficiency approach does not include the societal views on unacceptable risks (NRC (2014)).

The dilemma between efficiency and equity is also found in fields others than risk management, such as decision-making about infrastructure construction (Albalate et al. (2012); Joshi & Lambert (2007); Yamano & Ohkawara (2000)). Though in these cases the definitions of equity and efficiency are slightly different, the philosophy and the dilemma between both concepts remain the same.

3. Review of risk reduction indicators

As explained in the previous section, different risk reduction principles can be followed to guide safety management. Risk reduction indicators can be a useful tool to prioritize risk reduction alternatives according to these principles. These indicators are obtained from the effect a measure has on infrastructure risk and from its implementation and maintenance costs. In this section, different risk reduction indicators are presented and their relation to the risk reduction principles is explained. The main risk reduction indicators found in literature are:

- **Cost per Statistical Life Saved (CSLS):** This indicator is used to analyze risk management measures (HSE (2001)) in numerous fields such as aerospace (Stewart & Mueller (2008)), health science (Lutter et al. (1999); Ramsberg & Sjöberg (1997)), soil pollution (Khadam & Kaluarachchi (2003)), dam safety (ANCOLD (2003)) and road traffic safety (de Blaeij et al. (2003)). This indicator shows how much it costs to avoid each potential loss of life as a result of infrastructure failure when applying a measure. Its value is obtained through the following formula:

$$\text{CSLS} = \frac{C_a}{R_S^{base} - R_S^{mea}} \tag{4}$$

Where R_S^{base} is the risk expressed in loss of lives for the base case, R_S^{mea} is the risk in lives after the implementation of the measure and C_a is the annualized cost of the measure that includes its annualized implementation costs, annual maintenance costs and the potential changes in operation costs generated by the adoption of that measure.

CSLS compares costs with societal risk reduction, so when considering several measures, the measure with a minimal value of this indicator will be the one that employs the resources in a most efficient way. Therefore, this indicator is based on the principle of societal efficiency.

- **Economic Cost-Benefit Ratio (ECBR):** This indicator (Bowles (2004); Parker (1987)) arises from the comparison of the costs of a measure with the benefits on the economic risk reduction resulting from its implementation. According to the formula used in this paper, the lower this indicator is, the better the measure is.

$$\text{ECBR} = \frac{C_a}{R_E^{base} - R_E^{mea}} \tag{5}$$

- **Adjusted Cost per Statistical Life Saved (ACSLS):** This indicator (ANCOLD (2003); Bowles (2001)) has the same structure as CSLS but introduces an adjustment of the annualized cost to consider the economic risk reduction generated by the implementation of the measure. It is obtained with the following equation:

$$\text{ACSLS} = \frac{C_a - (R_E^{base} - R_E^{mea})}{R_S^{base} - R_S^{mea}} \tag{6}$$

Where R_E^{base} is the economic risk of the infrastructure for the base case and R_E^{mea} is the economic risk after the implementation of the measure.

ACSLS is usually used to apply the ALARP (As Low as Reasonably Practicable) (Bowles (2004); HSE (2001)) criterion, by indicating that as long as tolerability recommendations are respected, a measure can be rejected if it is not cost-efficient enough. ANCOLD's Bulletin 112 (Bowles et al. (1999)) contains a simple example of measure prioritization for a portfolio of dams by using ACSLS to apply the ALARP criterion.

ACSLS is focused on societal and economic efficiency, which are also the principles followed in a Benefit-Cost Analysis. In this analysis, the chosen alternative would be the one with the highest net benefits (Baecher et al. (1980); NRC (2014)). In annualized terms, net benefits are defined with the following equation:

$$\text{NB} = (R_E^{base} - R_E^{mea}) + VPF \cdot (R_S^{base} - R_S^{mea}) - C_a \tag{7}$$

Where VPF is the Value per Fatality applied. If the two previous equations are combined, the following relation is obtained:

$$\frac{NB}{R_S^{base} - R_S^{mea}} = VPF - ACSLS \tag{8}$$

As can be observed in the previous equation, net benefits are zero when ACSLS is equal to the value per fatality. Furthermore, the lower the ACSLS is, the higher the net benefits are, although these two approaches can produce different prioritization sequences due to the $R_S^{base} - R_S^{mea}$ term. The main advantage of using ACSLS to evaluate risk reduction measures instead of Benefit-Cost Analysis is that the controversial issue of defining a Value Per Fatality (citeViscusi2003) is avoided .

In addition to the former risk reduction indicators, it is also possible to directly use the risk reduction of individual, societal or economic risk produced by the mitigation measures (Bohnenblust (1998); Bowles (2004); Khadam & Kaluarachchi (2003)). In order to compare these possibilities with other risk reduction indicators in a homogenous way, the authors have put them in indicator form: **Individual Risk Decrease Index (IRDI), Societal Risk Decrease Index (SRDI) and Economic Risk Decrease Index (ERDI)**. For instance, the proposed form for the IRDI indicator is:

$$\text{IRDI} = \frac{1}{R_I^{base} - R_I^{mea}} \tag{9}$$

Where R_I^{base} is the individual risk for the base case and R_I^{mea} is the individual risk after implementing the measure. The same structure is followed for SRDI (with societal risk) and ERDI (with economic risk). According to this structure, the lower these indicators are, the better the measure is.

Finally, the authors propose two risk reduction indicators that allow the combination of economic costs with failure probability (which is strongly related to individual risk) and therefore the establishment of a relation between efficiency and equity:

- **Cost per Statistical Failure Prevented (CSFP):** This indicator expresses how much it costs to avoid infrastructure failure. The lower this value, the better the measure is. It is calculated as follows:

$$\text{CSFP} = \frac{C_a}{p_f^{base} - p_f^{mea}} \tag{10}$$

  Where p_f^{base} is the annual failure probability for the base case and p_f^{mea} is the failure probability after the measure implementation.

  In many critical infrastructures (nuclear plants, large dams...), certain types of failures (catastrophic failures) almost always produce fatalities. In these cases, failure probability may be used as a proxy of individual risk and CSFP may be used as a proxy indicator of equity. When applying this indicator to decision-making the authors recommend considering a two-step process. When individual risk is not tolerable, the CSFP is used. Once individual risk is below the tolerability level, then efficiency based indicators such as CSLS or ACSLS may be more convenient.

- **Adjusted Cost per Statistical Failure Prevented (ACSFP):** This indicator presents the same form as CSFP but introduces an adjustment on the annualized cost to consider the reduction of economic risk produced by the implementation of the measure. It is calculated with the following formula:

$$\text{ACSFP} = \frac{C_a - (R_E^{base} - R_E^{mea})}{p_f^{base} - p_f^{mea}} \tag{11}$$

This indicator is strongly related to the principle of economic efficiency and, as with CSFP, in some cases it can also be used to measure equity. A two-step approach like the one described for the CSFP is also recommended for the ACSFP.

Figure 1 uses a Venn diagram to visualize the relationship between indicators and principles described in this section.

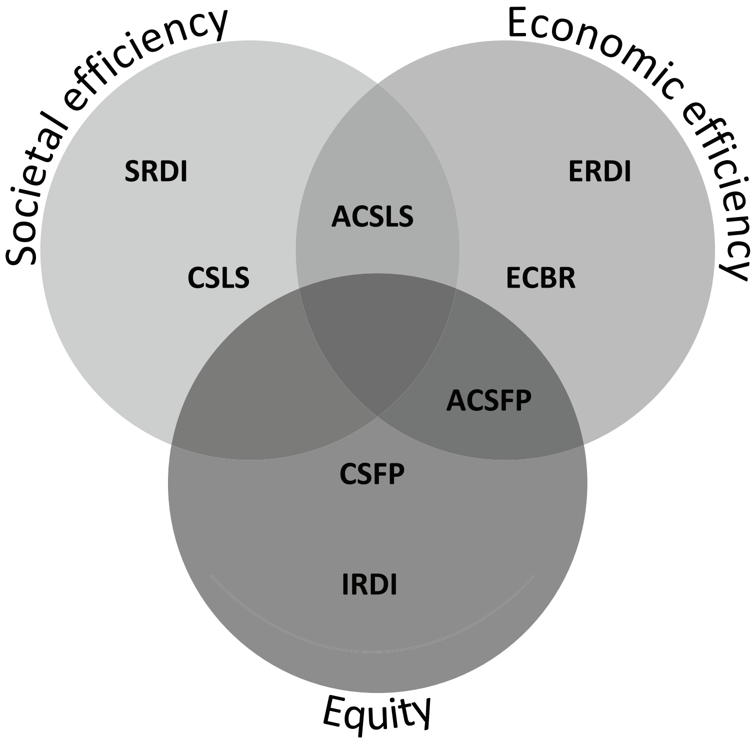

Figure 1. Venn diagram showing the relationship between risk reduction indicators and efficiency and equity principles.

4. Obtaining and assessing implementation sequences of risk reduction measures from risk reduction indicators

4.1. *Obtaining implementation sequences*

The relations explained in the previous section between risk indicators and risk reduction principles are used to obtain implementation sequences of risk reduction measures that follow these principles. These sequences are combined with the tolerability criteria to support a risk informed decision making process.

Once a risk model for the base case and for each risk reduction measure is set up, it is possible to calculate all risk reduction indicators for all measures. With this information, whichever measure has the best value of the preferred indicator can be picked up to be implemented in the first place. Then, the analysis is repeated assuming the first measure has already been implemented (in order to capture in an adequate way possible nonlinearities in the superposition of measures). By following this process iteratively a measure implementation sequence emerges, which is optimal[1] with regard to the employed criterion.

[1]Under certain circumstances, due to nonlinearities in the application of risk reduction measures, it is possible that this strategy will not yield the absolute optimum sequence. In these cases, the optimum sequence can still be obtained, but it is computationally more costly. However, the sequence obtained with the simple iterative strategy is typically either optimal or very close to optimal and will therefore be used throughout the paper.

4.2. *Variation curves*

Variation curves are graphical representations of the results obtained when defining a sequence of measures implementation. These curves show how risk or failure probability varies according to the number of measures implemented or their cost. On the y axis, aggregated risk of the analyzed infrastructures is plotted. On the x axis, either implementation step or accumulated costs are plotted. Also, when costs are plotted, two types of costs can be used: annualized costs (annualized implementation costs + annual maintenance costs + changes in annual operation costs) or annualized and adjusted costs (total annualized costs - decrease in annual economic risk). Figure 2 shows a conceptual representation of this kind of curves.

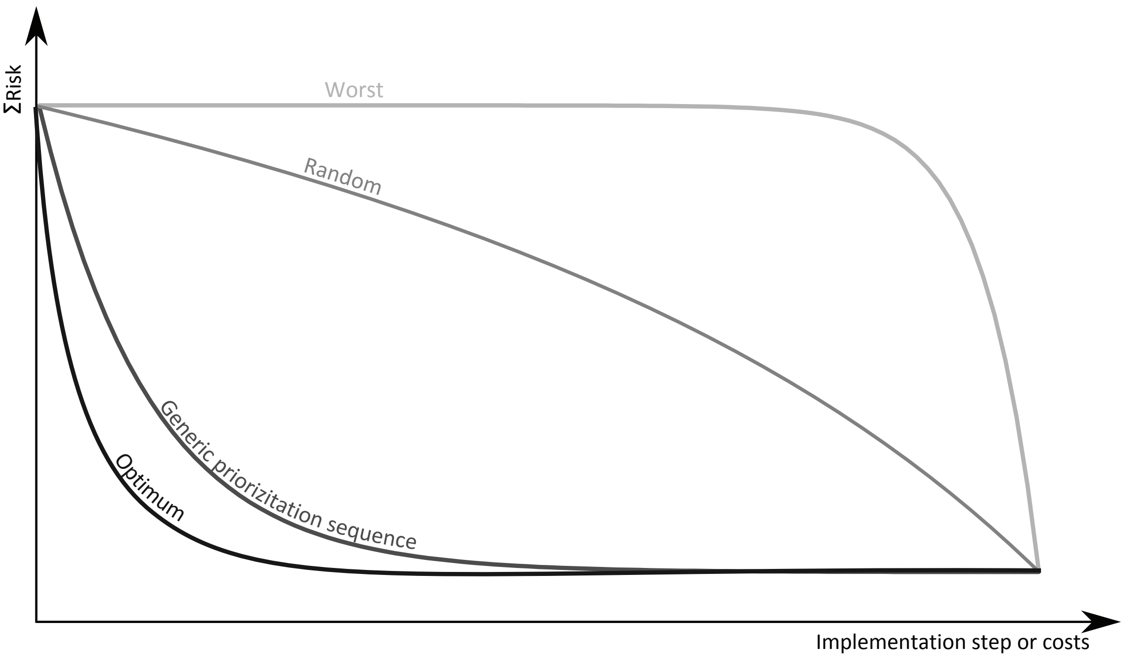

Figure 2. Generic representation of a variation curve showing four different prioritization sequences.

In this figure, each line represents the risk variation for a different prioritization sequence. In this type of curves, the best prioritization is given by the curve that approaches the X axis first, that is, the one that reduces risk or failure probability at a lower cost or with a lower number of implemented measures. Figure 2 shows four different types of variation curves:

- **Generic prioritization curve:** represents the usual shape presented by measure implementation sequences when obtained by applying a risk indicator.
- **Optimal curve:** Depending on the axes defined in the variation curve, there is an optimal measure implementation sequence. This sequence is the one that produces a more significant risk reduction or failure probability reduction at a lower cost or with a lower number of steps. Table 1 defines which variation curve produces the optimal sequence for each indicator (under certain linearity assumptions). As this table shows, each indicator produces an optimal curve in a different variation curve.
- **Worst curve:** This is the usual shape these curves have when representing for each sequence the measure with the worst value of risk indicator, that is, the least appropriate measure according to that factor. This curve and the optimal one delimit the space where all variation curves of all possible measure implementation sequences lie.
- **Average random curve:** This curve represents an average shape of variation curves when no particular risk indicator is followed to define the implementation sequence and instead, measures are chosen randomly.

Optimal Risk indicator	Variation graph X axis	Y axis
CSLS	Annualized measures cost	Societal risk
ACSLS	Annualized and adjusted measures cost	Societal risk
ECBR	Annualized measures cost	Economic risk
IRDI	Implementation step	Individual risk
SRDI	Implementation step	Societal risk
ERDI	Implementation step	Economic risk
CSFP	Annualized measures cost	Failure probability
ACSFP	Annualized and adjusted measures cost	Failure probability

Table 1. Variation curves where each risk indicator produces the optimal result.

It is worth noting that all curves share the same origin point (current situation of the set of infrastructures) and the same final point (situation of all infrastructures when all risk reduction measures are implemented). This responds to the fact that what is being decided is not which measures to adopt but in which order.

4.3. *Assessing the closeness to theoretical best of a measure implementation sequence*

In order to assess how "good" a measure implementation sequence is, some kind of metric must be used. Next, an index is proposed to accomplish this, the Closeness to Theoretical Best (CTB). It measures how close a prioritization sequence is from the theoretical best, which would consist in reducing all the risk in the first step, and is usually unachievable. In general, a sequence is better than another one if it reduces risk faster.

Moreover, the concept of how "good" a measure implementation sequence is varies according to the prioritization principle against which it is compared. A very appropriate sequence with regard to efficiency may not be so with regard to equity. Hence, not 1 but 3 CTB indexes have been devised in order to allow the assessment of efficiency and equity principles of a measure implementation sequence.

The optimal sequence according to the equity principle is the one that causes higher individual risk reduction at a lower measure implementation cost. Thus, the following CTB index is suggested for equity:

$$\mathrm{CTB}_{Eq} = 1 - \frac{\sum_{i=1}^{N} \Delta C^i \cdot (\log(R_I^i) - \log(R_I^{end})}{C_T \cdot (\log(R_I^{ini}) - \log(R_I^{end})} \tag{12}$$

Where N is the number of steps of the sequence, R_I^i is the individual risk for step i of the implementation sequence, R_I^{ini} is the initial individual risk, R_I^{end} is the individual risk of the last point of the sequence, ΔC^i is the increase in annualized cost produced after implementing measure i and C_T is the total annualized implementation cost of all measures.

If it were possible to achieve the final individual risk with a null cost (best possible case), the numerator would be 0, so CTB would equal 1. On the contrary, if individual risk was equal to the original value for all measure implementation costs (worst possible case), the denominator and numerator would be the same, so CTB would be 0.

The differences of each point of the sequence relative to the final individual risk are obtained using logarithms. In this way, a decrease of an order of magnitude in risk is valued equally, irrespective of whether it is in a low or high risk range. This is in accordance with the common practice of showing FN and fN graphs in logarithmic scales.

The same structure has been followed to define a CTB index for the societal efficiency (replacing individual risk with societal risk) and for the economic efficiency (replacing individual risk by economic risk).

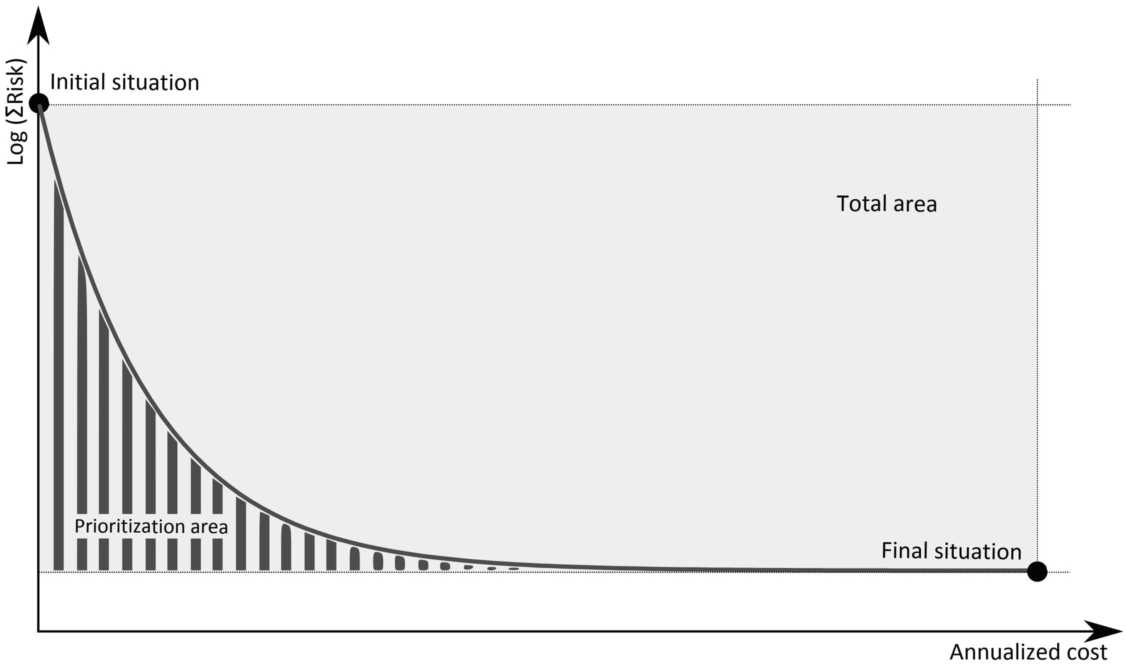

Figure 3. Definition of areas in variation curves in order to interpret CTB.

CTB indexes can have a graphical interpretation using the previously defined variation curves. The numerator of the suggested indexes is equal to the area under the curve in figure 3 (*Prioritization area*) whereas the denominator is equal to the total area of the rectangle defined by the initial and final points of the sequence (*Total area*). Thus, CTB can also be calculated with the following equation:

$$\text{CTB} = 1 - \frac{\textit{Prioritization area}}{\textit{Total area}} \tag{13}$$

The value of this index is 0 when the area under the variation curve is equal to the total area of the rectangle and its value is 1 when the area under the curve is null. For each analyzed principle, different variables are used in the axis of the variation curve to allow this graphic interpretation of CTB indexes:

- **Equity variation curve:** It represents annualized cost on the X axis and failure probability on the Y axis.
- **Societal efficiency variation curve:** It represents annualized cost on the X axis and societal risk on the Y axis.
- **Economic efficiency variation curve:** It represents annualized cost on the X axis and economic risk on the Y axis.

5. Case study: Management of a portfolio of 27 large dams

Next, a case study is shown where all presented prioritization strategies can be compared. This case study concerns an existing group of 27 dams located in Spain belonging to the same owner and the implementation of the presented measures is currently being studied in order to improve safety. It is a very heterogeneous set of dams including structures of different typology (15 concrete gravity dams, 4 small diversion dams, 3 double-curve arch dams, 3 earthfill dams and 2 single-curve arch dams), size (from 100.6 m to 11.6 m), construction year (from 1923 to even one currently under construction) and reservoir volume (from 641 hm^3 to 0.2 hm^3).

The starting point for this case study are the results obtained in a Quantitative Risk Analysis performed on each dam. As part of the analysis process, risk models were set up with iPresas software (iPresas (2014)) for each dam. These risk models are based on event trees(SPANCOLD (2012)) and they analyze the different ways in which a dam can fail (failure modes) calculating their associated probabilities and consequences. Input data in the risk models were elaborated during three years and they are the result of dams technical documents, working group sessions and numerical models. Risk models were elaborated for normal and hydrological loading scenarios and they include:

- Flood events probability.
- Probability of outlets availability for flood routing.
- Pool water levels probability.
- Flood routing results.
- Fragility analysis results for each failure mode. Fragility curves of different failure modes are combined using Common Cause Adjustment techniques(SPANCOLD (2012)).
- Loss of life and economic consequences estimation results based on hydraulic models. Economic consequences for failure cases also include the cost of losing the dam.

Detailed procedures followed to develop these risk models can be found in Altarejos-García et al. (2012); Ardiles et al. (2011); Serrano-Lombillo et al. (2012a,b). Figure 4 shows an example of one of the risk models.

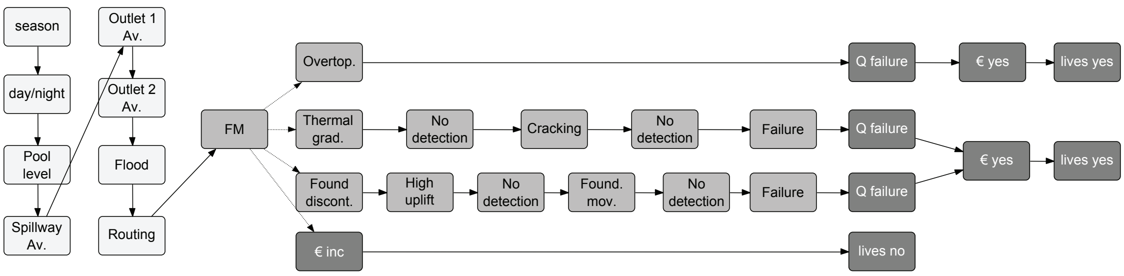

Figure 4. Risk model of one of the studied dams.

A total number of 93 measures were studied for the 27 analyzed dams. These measures came from a list of actions already planned to a higher or lower degree by the operator to improve dam safety along with the new needs revealed by the results of the Risk Analysis. Proposed measures are not general measures for all the dams but each one is planned to be applied only in one dam. Table 2 summarizes the risk reduction measures. As can be noticed, there is a great variety, with measures being of both structural and non-structural nature.

Structural measures		Non-structural measures	
Improve gates realiability	8	Emergency Action Plan (EAP)	23
Improve foundation condition	8	EAP + com., edu. and coord.	23
Improve dam body	8	Improve monitoring system	5
Renew gates and valves	5	Additional freeboards	4
Reinforce parapet wall	3		
Increase spillway capacity	3		
Additional outlet works	2		
Improve stilling basin	1		

Table 2. Summary of analyzed risk mitigation measures for the group of 27 dams.

Each proposed measured was budgeted by estimating implementation costs and maintenance and operations costs resulting from this implementation. Following Spanish recommendations on hydraulic infrastructures management (MMARM (2001)), the implementation cost of each measure was annualized by distributing it along its lifespan with a discount rate of 5%. Then, the annual maintenance and operation costs were added to the annualized implementation cost. In this way, the total cost of every measure was expressed in monetary units (in this case, euros) per year.

Different measure implementation sequences were obtained by using all of the risk reduction indicators defined in Section 3 as prioritization criteria. When doing these calculations, individual risk was assumed to be equal to failure probability. This is a usual hypothesis in large dams (USBR (2011a)) as the ones studied in this case, since dam failure would almost certainly result in at least one fatality.

Incremental consequences were used to calculate societal and economic risks. Incremental consequences are incremental losses or damage, which dam failure might inflict on upstream areas, downstream areas, or at the dam, over and above any losses which might have occurred for the same natural event or conditions, had the dam not failed (ANCOLD (2003)). Risk is then known as incremental risk and is usually employed in dam safety (ANCOLD (2003); USACE (2014)).

According to USACE (2014), the proposed tolerability limit for individual risk is 10^{-4}. Therefore, a sequence combining ACSFP (with failure probabilities higher than 10^{-4}) and ACSLS (with failure probabilities lower than 10^{-4}) was also calculated, following the recommendations in section 3. This sequence is labelled ACSLS/ACSFP in the following figures and tables. Furthermore, an additional sequence was obtained choosing in each step the measure with the highest Net Benefits according to a Benefits-Cost analysis. For this purpose, a Value per Fatality of 1.26 M€ was used according to HSE (2001) recommendations. This sequence is labelled BCA.

Before obtaining indicator based prioritizations, a sequence corresponding to a random average case was calculated to compare with the implementation sequences obtained from the application of the different prioritization criteria. This case represents the results of the average risk variation when no risk indicator is followed to define the sequence, but instead measures are chosen randomly at every step. In order to determine this random average case 1,000 different random prioritization sequences were generated. The average case was then determined by obtaining the average risk variation of all of them for each implementation step. Figure 5 shows the results in the efficiency variation curve. In this figure, they have been compared with the sequence obtained using the optimum indicator (CSLS as indicated in Table 1) and with the sequence obtained with the worst indicator (inverse of CSLS). As can be observed, the sequence obtained with the optimum indicator performs much better than any of the random sequences, since it reduces risks with lower costs. This fact justifies the use of risk reduction indicators to obtain sequences of risk reduction measures more efficiently. It would be necessary to compute many random sequences to find the optimum without these indicators since there are $93! \approx 10^{144}$ possible sequences of measures.

Next, using all indicators presented in this paper different measure implementation sequences were obtained for the set of dams under analysis. Figure 6 shows equity, societal efficiency and economic efficiency variation curves for the different calculated indicators.

In each variation curve the indicator that produces a better sequence (more significant risk reduction at a lower cost) is different. In the case of the societal efficiency curve, the optimal sequence is given by the indicator CSLS, for the economic curve, it is ECBR and in the case of equity, CSFP. Additionally, the worst implementation sequence was defined for each case, choosing at each step the measure with the highest value of the indicator that produces the optimal sequence. These sequences are also shown in figure 6.

The CTB indexes defined in section 4.3 were then used to numerically analyze the goodness of the implementation sequences according to each prioritization principle. As table 3 shows, the indicators that produce better values of societal efficiency are CSLS and ACSLS. The indicators producing higher economic efficiency are ECBR and ACSFP. Finally, the indicators producing better equity values are CSFP and ACSFP.

As can be seen, indicators produce good results for the CTB index of the principle on which

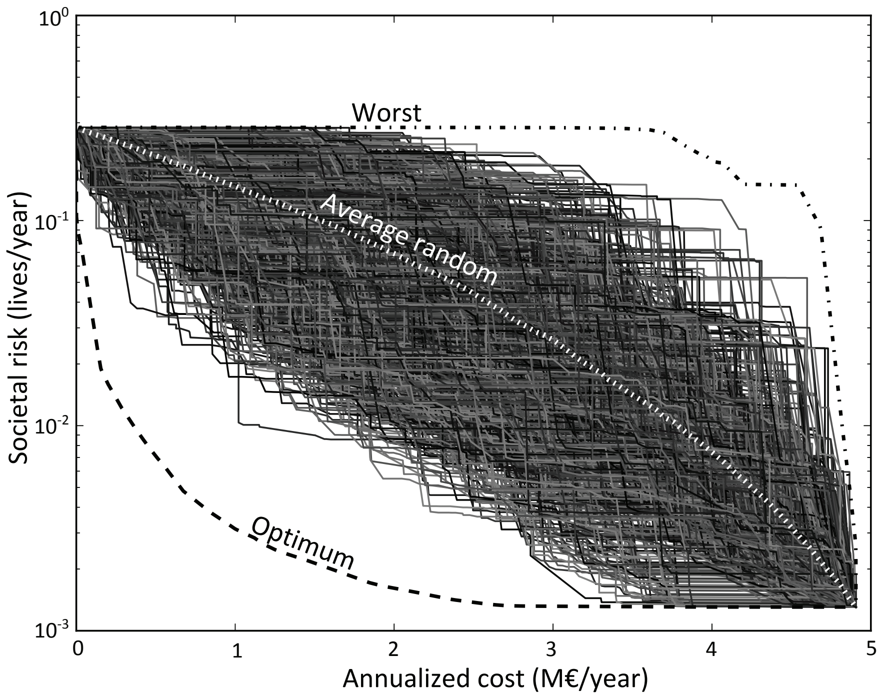

Figure 5. Results of the 1000 randomly calculated cases and average random case represented in a societal efficiency variation curve.

Indicator	Economic efficiency CTB	Societal efficiency CTB	Equity CTB
CSLS	81.2%	**90.0%**	73.1%
ACSLS	87.7%	87.5%	79.0%
ECBR	**94.6%**	62.0%	91.6%
IRDI	86.9%	56.1%	89.4%
SRDI	71.8%	83.9%	59.1%
ERDI	90.5%	57.6%	88.6%
CSFP	91.7%	55.3%	**93.5%**
ACSFP	92.7%	55.3%	92.2%
ACSFP/ACSLS	92.1%	79.5%	91.1%
BCA	82.7%	72.5%	71.3%
Random average	38.2%	38.3%	34.4%
Worst societal ef.	5.6%	**3.6%**	9.8%
Worst economic ef.	**5.2%**	37.2%	4.2%
Worst equity	5.5%	36.3%	**4.0%**

Table 3. CTB indexes for each risk indicator.

they are based. Besides, according to the obtained results, indicators based on equity produce good economic efficiency and vice-versa. This is a specificity of the chosen case study and it is due to the fact that none of the introduced measures directly diminishes economic consequences and that failure probability reductions produce a similar change of economic risk. Therefore, the sequences defined by indicators IRDI and ERDI present very similar CTBs. Additionally, both ACSFP and ACSLS have higher economic efficiency than CSFP and CSLS respectively, since they include economic risk on their formulation. In order to compare graphically how societal efficiency and equity principles are addressed for each indicator, the CTB indexes obtained for both principles have been represented in figure 7.

Finally, on the one hand, the results of the BCA sequence show that only the first ten measures produce positive net benefits so are justified from the Benefit-Cost point of view. The global an-

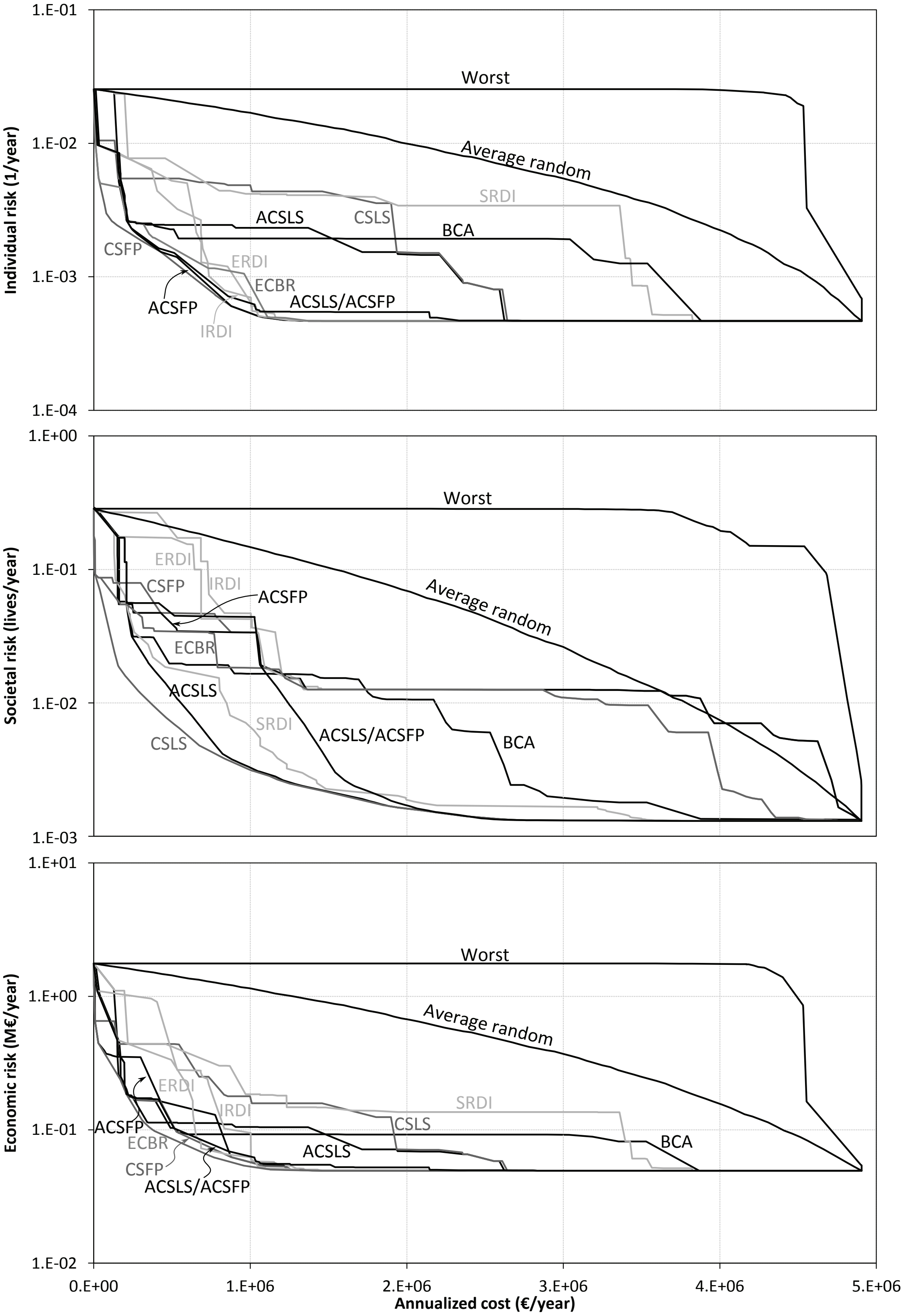

Figure 6. Implementation sequences for different risk reduction indicators represented in the variation curves for equity, societal efficiency and economic efficiency principles.

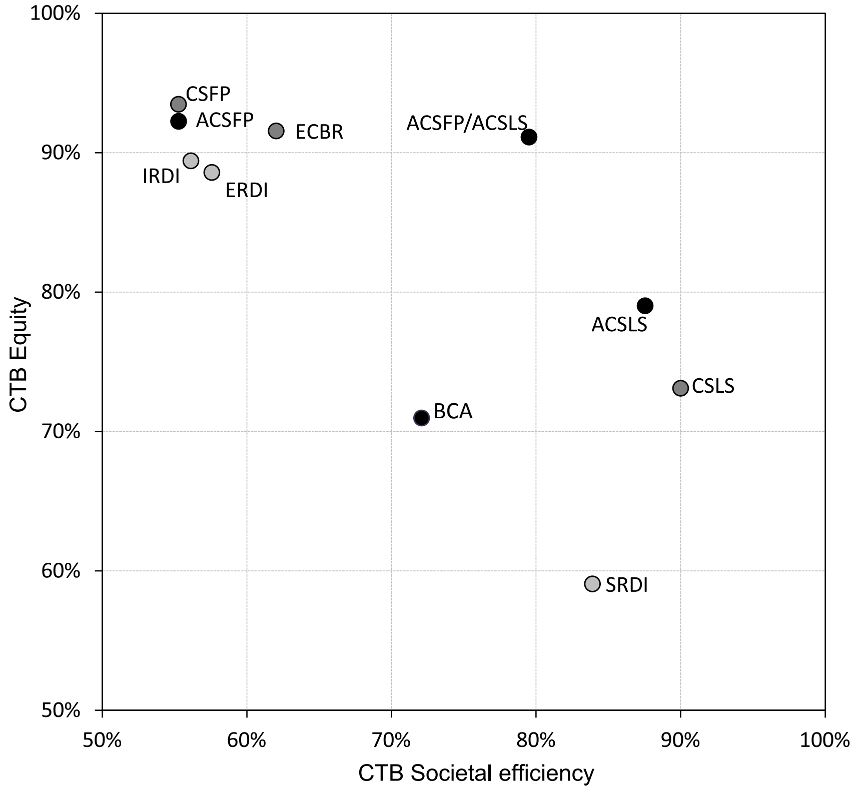

Figure 7. Comparison between efficiency CTB and equity CTB for each risk indicator.

nualized cost of these measures is 215,688€. On the other hand, the results of the ACSFP/ACSLS sequence (the only sequence that combines equity and efficiency) show that USBR (2011a) and USACE (2014) tolerability guidelines, are met in all the dams when 31 measures are implemented, being the global annualized cost of these measures 1,511,697€. This comparison shows that decisions considering equity and tolerability criteria can include measures that are not justified from a pure efficiency point of view.

6. Discussion and conclusions

The paper presents a rationale for prioritizing risk reduction measures when investing in the safety of a portfolio of hydraulic critical infrastructures. The principles framing such rationale go from how effective the investments in remedial actions are, their costs and benefits or the possible constraints on how they may comply with some well-established general statements on the hierarchy of risk controls, such as the more individually focused equity or the more socially and economically concerned efficiency.

The basis of the methodology relies on the fact that the relative merits of the options a decision maker may have can be quantified by examining such principles through a number of indicators, some of them originally developed, tested and used by the authors with a portfolio of 27 large dams. From the issues of applying the methodology and indicators to inform the safety management of such portfolio of dams, particular and general conclusions have been identified and are herein summarized.

Starting with the more specific ones, the main discussions and conclusions arising from the study presented in the paper are:

- The procedure outlined in this paper, based on risk reduction principles and its indicators, allows obtaining and assessing measure implementation sequences in a clear and simple way from quantitative risk results. This procedure reduces significantly the required computations to obtain an optimum prioritization sequence in complex portfolios with many proposed measures. It also allows to track the impact of different principles, to combine them and to compare them.

- It does not matter how quantitative risk results are built: as long as the former are reliable, it does not make any difference in the procedure presented in this paper.
- Furthermore, the use of the Closeness to Theoretical Best (CTB) index proposed in this paper can be a useful way to make quantitative comparisons between different sequences.
- As demonstrated in the case study, prioritization of different structural and non-structural measures in a consistent and justifiable way can be accomplished by using the results offered by risk models, even in heterogeneous groups of dams.
- The existing conflict between equity and tolerability criteria versus pure efficiency is highlighted with the results of the case study. On the one hand, tolerability criteria and equity can promote alternatives which do not maximize benefits. On the other hand, a pure efficiency approach does not include societal views on unacceptable risks and individuals' rights to certain levels of protection. A compromise between these approaches can be reached combining different risk indicators or different prioritization sequences.
- In practice, each critical infrastructure operator will choose the principles and tolerability limits that reflect its values and objectives more adequately. Besides, management of critical infrastructure safety actions can incorporate many factors of administrative, societal and economic order, difficult to quantify and that might condition decision-making. Within this context, measure implementation sequences based on risk results provide a valuable information to decision-making and in some cases can be an input to a more global multicriteria analysis.

From a broader perspective on how this type of approach will impact the safety management of any hydraulic critical infrastructure, some insights arising from this paper are:

- Having a more rational and structured quantitative information, able to capture different values depending on the context (country, regulatory framework, liability, business culture, etc.) will be in the benefit of any owner or decision maker regardless the specific type of infrastructures managed.
- It will also enable a clear and transparent way to communicate options in decision making both internally (to the upper management of a particular entity) and externally (to politicians and the general public), which is a premise for good governance.
- Though the methodology utility has been proved for a portfolio of critical hydraulic infrastructures such as large dams, it can be easily envisioned how it would be possible to tailor it for different types of civil infrastructures where best practices already include risk identification, calculation, evaluation, assessment and management (i.e. transportation, energy production, etc.)

Finally, major challenges to be addressed when using the suggested approach to inform decision making are, among others, to better understand and tackle the role of different sources of uncertainty (natural, epistemic etc.) as well as to find a consistent manner to evaluate time issues such as the expected time to complete a corrective action and the balance between short term and long term actions.

Acknowledgements

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Annex 2

Review, Analysis and Application of Existing Risk Reduction Principles and Risk Indicators for Dam Safety Management

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Review, analysis and application of existing risk reduction principles and risk indicators for dam safety management

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Summary

Risk Analysis is a useful methodology to manage dam safety in an accountable and comprehensive way. Risk models are used to evaluate the effect of different risk reduction measures. In order to prioritize between these measures, several strategies, indicators and recommendations exist. The information needed to follow these recommendations can be computed from risk models. In this paper, different risk indicators and strategies are analyzed. They have been obtained from recommendations of different international organizations and researches and are based on risk reduction principles, mainly equity and efficiency.

These strategies have been applied and compared to prioritize measures in a real portfolio of dams. For each strategy, a sequence has been obtained to implement different structural and non-structural measures. Finally, the relation between risk indicators, the principles they follow and the obtained implementation sequences has been analyzed.

Introduction

Large dams are critical infrastructures whose failure could produce important societal and economic consequences. This failure has a probability, although it is usually very low. Therefore, these infrastructures have an associated risk that must be studied and managed. Risk Analysis is a suitable methodology to manage dam safety [5], [9], since it integrates available information about hazards, vulnerability and consequences [19]. With this methodology, decision-making for dam safety is justifiable, objective and clear.

In this paper, a process is presented to prioritize risk reduction measures in a group of dams. This process applies risk results obtained with risk models to obtain a measures implementation sequence. It is based on risk indicators and risk reduction principles, mainly efficiency and equity.

First, some previous concepts are explained and the structure of the process followed to obtain measures implementation sequences is explained. Second, the main risk reduction principles are explained and analyzed. Third, a revision of existing risk indicators is made to examine its relation with the risk reduction principles.

Finally, this process has been applied to support decision-making in an existing portfolio of 27 dams with 93 proposed risk reduction measures.

Previous concepts

Risk is the combination of three concepts: what can happen, how likely it is to happen and what are its consequences [14]. When risk concepts are applied to dam safety, what can happen is the dam failure, which has a probability of occurrence and some adverse consequences. Risk can be defined and quantified in very different ways [13]. Thereby, the definitions for risk concepts used in this article are:

- Individual risk (R_I): It is defined as the probability that an average unprotected person, permanently present at a certain location, is killed due to dam failure [4]. It is usually an annualized probability, so its units are years^{-1} and can be obtained with the following formula:

  $$R_I = \int p(e) \cdot p(f|e) \cdot p(d \geq 1 | f, e) \cdot de \qquad (1)$$

  Where *p(e)* is the probability of occurrence of a potentially dangerous event *e*, *p(f/e)* is the probability of dam failure *f* due to this event and *p(d≥1/f,e)* is the probability of having at least one fatality due to the dam failure *f*.

  In a large dam located upstream populated areas, the third probability of this equation is almost 1, since the flood produced by the dam failure would probably produce some fatalities downstream. In these cases, the individual risk is equivalent to the dam failure probability [27].
- Societal risk (R_S): This risk is obtained when dam failure probability is combined with dam failure social consequences. These consequences are generally expressed in life loss terms, so societal risk units usually are fatalities/year. In general, societal risk is quantified using annualized life loss [6], which can be obtained with the following formula:

  $$R_S = \int p(e) \cdot p(f|e) \cdot c_S(f, e) \cdot de \qquad (2)$$

Where $c_S(f,e)$ are the societal consequences (generally life loss) produced by the dam failure f due to event e.

- Economic risk (R_E): This risk is obtained when dam failure economic consequences are analyzed [13]. These consequences are expressed in economic terms, so economic risk units usually are economic units/year. In general, economic risk is quantified using annualized economic loss [6], which can be obtained with the following formula:

$$R_E = \int p(e) \cdot p(f|e) \cdot c_E(f,e) \cdot de \quad (3)$$

Where $c_E(f,e)$ are the economic consequences produced by the dam failure f due to event e.

Following these formulas, risks are usually computed using risk models [22], [28], which represent the variables that influence dam's safety and their relations. These variables are used to estimate dam failure probability and its consequences.

In dam risk management, societal and economic risks are usually obtained using incremental consequences. These consequences are computed subtracting the consequences in the non-failure case to the consequences in the dam failure case. This is a common practice for dam risk management [2], [24], [26], because it allows taking into account only the part of the risk produced by the dam failure.

Risk management based on risk reduction principles and risk indicators

In this article, the process shown in Figure 1 is applied to obtain sequences for risk reduction measures implementation in a dam portfolio. This process is based on risk reduction principles and risk indicators. It follows the recommendations for risk management of some of the main international dams' organizations and managers, like HSE [10], ANCOLD [2], ICOLD [11], USACE [17], [26] and USBR [28].

First, risk is computed for all dams in the portfolio in the current situation. This risk is obtained using risk models, as explained in the previous chapter.

Second, risk results in the current situation must be evaluated. In this phase, judgments and values are introduced in the process [11]. Risk is defined as unacceptable, tolerable or broadly acceptable [10] based on international risk tolerability guidelines:

- When risk is unacceptable, risk reduction measures must be proposed and implemented.
- If the risk is tolerable, it is also recommended to propose risk reduction measures. In this case, the measures are analyzed and its implementation is only recommended if they fulfill the ALARP (As Low As Reasonably Practicable) criterion [6], [7]. This criterion is evaluated with risk indicators based on measure's efficiency, as it is explained in the risk indicators section of this paper.
- If the risk is broadly acceptable, it is not necessary to implement risk reduction measures. This is not usual for large dams' risk.

Some examples of international tolerability guidelines for dams can be found in the bibliography [2], [20], [26], [27].

Therefore, the third step of this process is to define potential risk reduction measures in the portfolio. Risk is computed again using the corresponding risk model and taking into account the effect of each measure in dam's safety.

The next step is to compare risk in the current situation with risk in the situation with the measure implemented. This comparison can be made using risk indicators, which are based on risk reduction principles, mainly efficiency and equity. These principles are explained in the following section. The risk reduction principle followed to define a measures' sequence depend on the risk indicator chosen in this step to compare the measures.

When the risk indicator is computed for all measures, they can be ranked according to these results. This risk indicator is used then as a prioritization criterion. The first measure of this ranking is chosen as the first step in the implementation measures sequence.

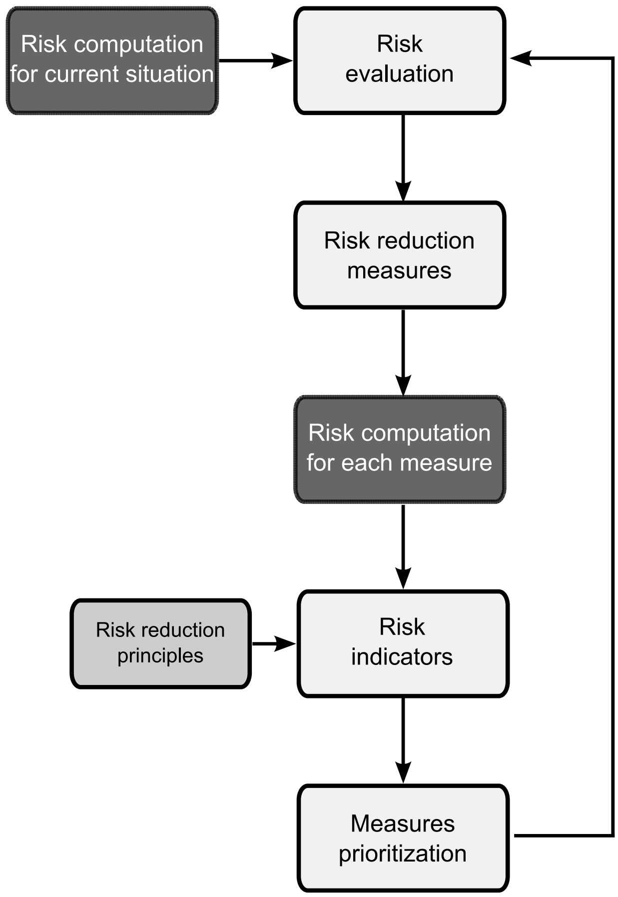

Figure 1: Process to obtain risk reduction measures sequences based on risk results.

Next, the process is repeated defining the current situation as the situation with the chosen measure implemented and analyzing the effect of each proposed measure. If this process is consecutively followed, a measures sequence is obtained to manage the risk in the dams' portfolio.

Risk reduction principles

When the Risk Analysis methodology is used to manage dam risk, the most important part is the decision-making process [10]. As explained in the previous section, this process can be based on risk reduction principles. In general, two principles [10], [11] can be followed:

- Equity: This principle is based on the right of individuals and society to be protected to a certain level. Its application is based on individual risk (Equation 1), which represents the level of protection of all the individuals in a society.
  The equity concept is linked to an individual risk limit, which defines the level of protection that must be reached for all the individuals. This principle can be applied when the individual risk is above this limit. USACE recommends an individual risk limit for dam safety of 10^{-4} [26]. Another example of individual risk limit is introduced in the Dutch legislation [29].
- Efficiency: This principle is related with the need that society has to distribute and use its available resources in such a way as to gain maximum benefit. When different measures are compared, the measure chosen according to the efficiency principle is the one that produces a higher risk reduction with a lower cost. This should be the predominant principle when the risk is tolerable. In this paper, the efficiency principle has been split in two principles:
  - Societal efficiency: When the risk that is analyzed is societal risk, usually expressed in life loss/year.
  - Economic efficiency: When the measure's efficiency is defined using the reduction in economic risk. This efficiency should only be prevalent when the dam risk is below the tolerability limits [5].

Hence, two different principles can be followed to support dam safety decision-making. The result of these principles can differ and produce some conflicts between them. An optimum measure from the equity point of view may be not sensible from an efficiency point of view.

The conflict between efficiency and equity is also common in fields different to risk analysis, like decision-making for construction of infrastructures [1], [30].

Review of existing risk indicators

Risk indicators can be used to quantify how a measure follows a risk reduction principle. These risks indicators are obtained using the measure's cost and the risk results for the initial situation and the situation with the measure implemented. The main risk indicators found in the bibliography are:

- CSLS (Cost per Statistical Life Saved): This indicator is used in very different fields for risk management, like aeronautic industry [25], medicine [16], soils contamination [15], dam safety [2] and road safety [8]. It shows how much it costs to save each statistical life by implementing a measure. Its value is obtained with the following formula:
  $$CSLS = \frac{C_{an}}{R_S^{ini} - R_S^{mea}} \quad (4)$$
  Where R_S^{ini} is the societal risk in the initial situation, R_S^{mea} is the societal risk in the situation with the measure implemented and C_{an} is the annualized cost of the measure during its lifespan, including the increment on the maintenance and operation costs. The units of this indicator are economic terms. The lower this value is the more efficient the measure is.
  CSLS compares costs with societal risk, so this indicator is based on the societal efficiency principle.
- ACSLS (Adjusted Cost per Statistical Life Saved): This indicator [2], [5] has the same structure as CSLS but uses adjusted cost to take into account the benefit due to the economic risk reduction. It is computed with the following formula:
  $$ACSLS = \frac{C_{an} - (R_E^{ini} - R_E^{mea})}{R_S^{ini} - R_S^{mea}} \quad (5)$$
  Where R_E^{ini} is the economic risk in the initial situation and R_E^{mea} is the economic risk in the situation with the measure implemented.
  This indicator is also used to analyze how efficient a measure is. In this case, it takes into account the reduction in economic and societal risk, so it is based on economic and societal efficiency. When a risk is tolerable, ANCOLD [2] suggests using this indicator to analyze if a measure is efficient and its implementation is recommended to fulfill the ALARP criterion. The values of ACSLS used to justify a measure implementation when the risk is just below the tolerability limits are:
  - Very strong justification: < 5 A$M.
  - Strong justification: 5 – 20 A$M.
  - Moderate justification: 20 – 100 A$M.
  - Poor justification: >100 A$M.
- CBR (Cost-Benefit Ratio): This indicator [6], [21] is obtained when the measures cost is compared with its risk reduction benefit. So, it is based on the

economic efficiency principle. According to the formula used in this paper (Equation 6), a measure is better when this value is lower.

$$CBR = \frac{C_{an}}{R_E^{ini} - R_E^{mea}} \quad (6)$$

Besides these indicators, risk results can also be used directly as risk indicators. Therefore, in each sequence step the measure that produces a higher risk reduction is chosen. Depending on the analyzed risk, three different indicators can be obtained:

- Minimize individual risk: In each step, the measure that produces a lower individual risk is chosen. In the bibliography, different examples [3], [15] can be found where individual risk is directly used as risk indicator for decision-making.
  When this indicator is used, the objective is reducing the individual risk, so it is based on the equity principle.
- Minimize societal risk: In this case, the measure that produces the highest societal risk reduction is chosen. Some examples where this indicator is used are [6], [15].
  This indicator is based on the social efficiency principle, since its objectives is reducing the societal risk.
- Minimize economic risk: This indicator is equivalent to the two other but analyzing the economic risk [6], [10]. Using directly the economic risk is based on the economic efficiency principle, although it does not take into account the measure cost.

After reviewing the existing risk indicators, it can be concluded that they can be very useful to evaluate if a measure is recommended from an equity or efficiency point of view. However indicators combining both principles have not been found, as it is shown in Figure 2, which shows the relation between the presented indicators and the risk reduction principles.

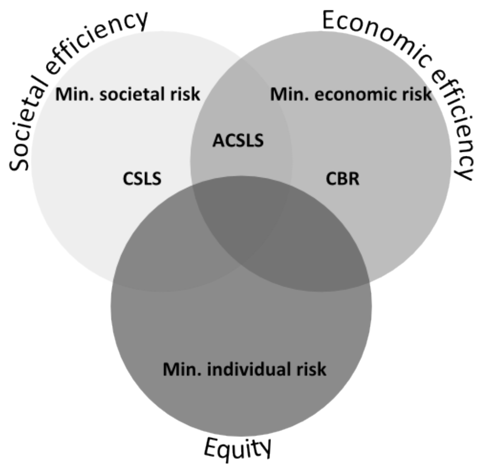

Figure 2: Relation between the reviewed risk indicators and the risk reduction principles.

Case study

In this paper, a process has been presented to obtain measures implementation sequences based on risk indicators and risk reduction principles. This process has been applied to prioritize measures in an existing portfolio of 27 dams belonging to a same owner. It is a very heterogeneous group of dams in size and age, as can be seen in Table 1. Furthermore, one of the dams is currently under construction.

TABLE 1: SUMMARY OF DAMS' CHARACTERISTICS.

Typologies	15 Gravity dams 4 Diversion dams 3 Double-curve arch dams 3 Earthfill dams 2 Single-curve arch dams
Construction year	From 1923 to currently in construction
Dam height	From 100.6 m to 11.6 m
Reservoir volume	From 641 hm^3 to 0.2 hm^3

In total, 93 risk reduction measures has been analyzed and prioritized. These measures are currently being studied to improve dam safety. Table 2 summarizes the proposed measures.

TABLE 2: SUMMARY OF MEASURES ANALYZED IN THE CASE STUDY.

Structural measures		Non-structural measures	
Improvement of gates reliability	8	Emergency Action Plan (EAP)	23
Improvement of foundation condition	8	EAP with Communication, Education and Coordination strategy	23
Improvement of dam's body	8	Improvement of monitoring system	5
Renewal of outlet works/spillway gates	5	New freeboard requirements	4
Reinforcement of parapet wall	3		
Higher spillway capacity	3		
New outlet works	2		
Improvement of stilling basin	1		
TOTAL	38	TOTAL	54

The main tools to manage risk in these 27 dams are the risk models that have been developed for them. Each dam has a risk model as a result of a Risk Analysis process. These models compute risks for the main failure modes in the dams and have been developed with the iPresas software [22], [23], [12]. Figure 3 shows an example of these risk models.

Measures implementation cost has been annualized along its lifespan with a discount rate of 5%, according to Spanish recommendations for hydraulic infrastructures [18]. Furthermore, the increment on maintenance and operation costs has been added to this cost.

When the effect of all the measures on dams risk has been analyzed, six different measures implementation sequences have been computed. They have been obtained following the process explained previously and using as prioritization criteria the six risk indicators explained in the previous section. To obtain these results individual risk has been considered equal to the dam failure probability, as it explained in the previous concepts section. Furthermore, risk indicators have been obtained using incremental risks.

Figure 4 shows how individual, societal and economic risks decrease when resources are spent on the proposed risk reduction measures for the six obtained sequences. The following conclusions can be reached observing these graphs:

- The best individual risk decrease for the same cost is produced by the sequence obtained with the minimum individual risk indicator. This sequence is the most appropriate from an equity point of view.
- The best societal risk decrease for the same cost is produced by the sequences obtained with the indicators CSLS, ACSLS and minimum societal risk. These sequences are the most appropriate from a social efficiency point of view.
- The best economic risk decrease for the same cost is produced by the sequences obtained with the indicators CBR and minimum economic risk. These sequences are the most appropriate from an economic efficiency point of view.

Furthermore, it can be observed that sequences with a good behavior from an equity point of view have also a good behavior from an economic efficiency point of view and *vice versa*. This is due to the kind of measures analyzed in this case, because there are no measures that modify the economic consequences nodes of the risk model. Therefore, a failure probability decrease produces an almost proportional decrease in the economic risk.

Finally, to understand how this kind of measures implementation sequences can support decision-making, the sequence obtained with the indicator ACSLS has been analyzed in detail. The ACSLS value for the measure implemented in each step is shown in Figure 5. In this graph, four different zones can be observed, delimited by the ACSLS limits proposed by the ANCOLD [2]. These limits have been converted to Euros in 2012:

- From the 1st to the 13rd steps in the sequence, all the measures are very strongly justified. Furthermore, all of them improve dams whose risk is above the tolerability limits.
- From the 14th to the 18th steps, the measures are strongly justified. These measures are applied to dams above and below the tolerability limits. In the second case, its implementation is justified due to the ALARP criterion.
- From the 19th to the 27th steps, the measures are moderately justified. In this case, only those measures that improve dams above the tolerability limits are completely justified. In the other cases, measures implementation depends on the available resources, following the ALARP criterion.
- From the 28h to the 93th steps, the measures are poorly justified. In this case, only those measures that improve dams above the tolerability limits are completely justified. In the other cases, measures implementation is weakly justified from an efficiency point of view, according to the ALARP criterion. The last measure that improves a dam above the tolerability limits is the 56th measure. From this point till the end of the sequence, all the dams are below the tolerability limits.

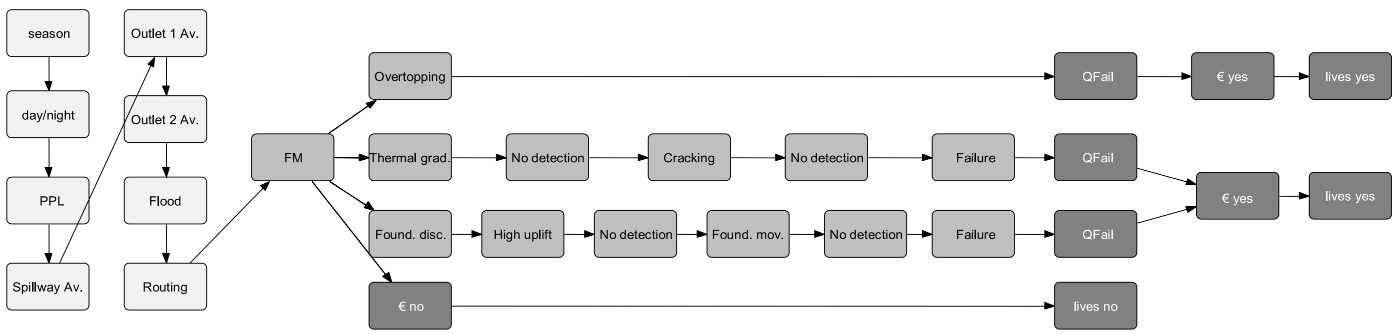

Figure 3: Risk model of one of the analyzed dams.

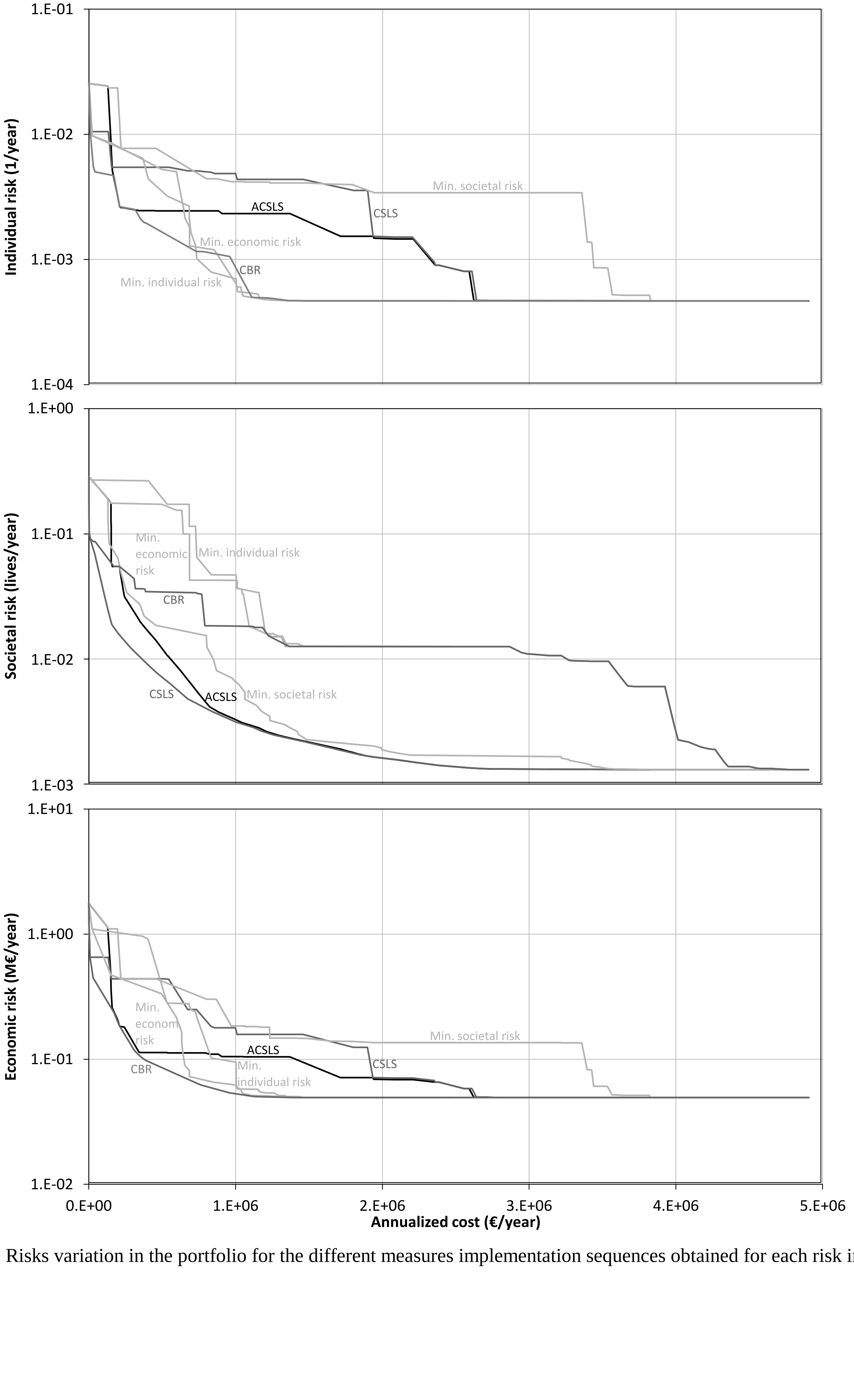

Figure 4: Risks variation in the portfolio for the different measures implementation sequences obtained for each risk indicator.

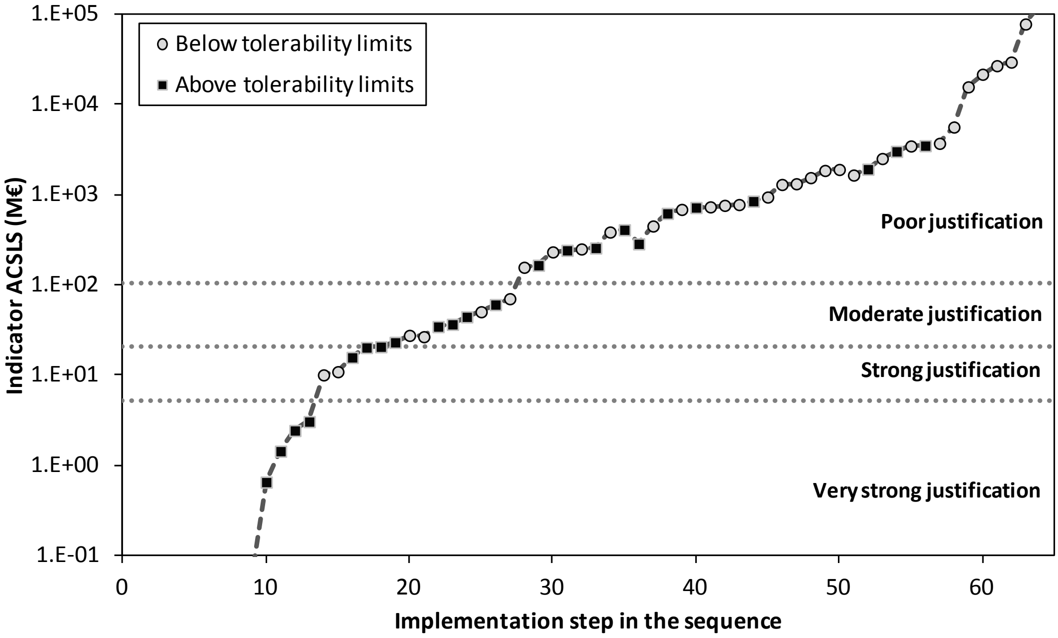

Figure 5: ACSLS variation for the implementation sequence obtained with the ACSLS indicator.

Conclusions

The main conclusions reached with this paper are:

- Risk Analysis is a methodology recommended by some of the most important dam organizations and owners to manage dam safety. In this methodology, the most important part is the decision-making process based on risk results.
- Risk indicators based on risk reduction principles can be very useful to obtain sequences of risk reduction measures. These sequences can be obtained following a simple process and are very useful to support decision-making in dam safety.
- Principles of efficiency and equity can guide decision-making for risk management. In some cases, these two principles can conflict, so it can be important to find an equilibrium between them.
- The revision made of existing risk indicators has shown that they follow one of these two principles, but there are not indicators to combine both of them.
- The case study has shown that these sequences can be easily obtained for a very heterogeneous portfolio of dams. 93 structural and non-structural measures have been prioritized with different risk indicators. Furthermore, the justification of each measure implementation can be analyzed using these results.

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Annex 3

A New Risk Reduction Indicator for Dam Safety Management Combining Efficiency and Equity Principles

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A new risk reduction indicator for dam safety management combining efficiency and equity principles

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Abstract

Large dams are critical infrastructures whose failure could produce high economic and social consequences. Risk analysis has been shown to be a suitable methodology to assess these risks and to inform dam safety management. In this sense, risk reduction indicators are a useful tool to manage risk results, yielding potential prioritization sequences of investments in dams portfolios. Risk management is usually informed by two basic principles: efficiency and equity. These two principles many times conflict, requiring a tradeoff between optimizing the expenditures and providing a high level of protection to all individuals. In this paper, the risk reduction indicator EWACSLS (Equity Weighted Adjusted Cost per Statistical Life Saved) is presented. This indicator allows obtaining prioritization sequences of investments while maintaining an equilibrium between equity and efficiency principles. In order to demonstrate its usefulness, it has been applied in a real world case study, a portfolio of 27 dams where 93 structural and non-structural investments are prioritized. The EWACSLS indicator is analyzed in detail and its results are compared with other existing risk reduction indicators, showing its flexibility and how it can be a very well balanced indicator for the purpose of prioritization of risk reduction measures.

Keywords

Dam safety, risk, risk management, infrastructure planning, decision making

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1. INTRODUCTION

Large dams are critical infrastructures whose failure could have high economic and social consequences. Worldwide state-of-the-practice recognizes the benefits of Quantitative Risk Analysis as a tool for informing dam safety management (ICOLD, 2005). This methodology allows supporting decision making in structural enhancements and other improvements in operation and maintenance, surveillance or emergency preparedness.

Risk analysis to inform dam safety management is generally contextualized within the HSE Tolerability of Risk (TOR) framework (HSE, 2001) for risk evaluation and management. This framework has been widely used worldwide to define risk management and dam safety programs (ANCOLD, 2003; SPANCOLD, 2012; USACE, 2014; USBR, 2011). According to this framework, two basic principles are generally used to guide decision making based on quantitative risk results (HSE, 2001; ICOLD, 2005):

- **Equity:** It is based on the premise that all individuals have unconditional rights to certain levels of protection.
- **Efficiency or utility:** It rises from the need society has to distribute and use its available resources in such a way as to gain maximum benefit.

These two principles can conflict, since what can be an optimal measure from the equity point of view may not be so from the efficiency point of view and vice versa. This dilemma between efficiency and equity is not only restricted to risk analysis and safety management, but it also occurs in many other fields related with decision making in the public sector. For instance, in general public investments (Albalate, Bel, & Fageda, 2012; Blackorby & Donaldson, 1977; Yamano & Ohkawara, 2000), the health sector (Bleichrodt, 1997; Dolan, 1998), the transport sector (Joshi & Lambert, 2007) the education sector (De Fraja, 2001; Dundar & Lewis, 1999) and the environmental sector (Linnerooth-Bayer & Amendola, 2000; Swisher & Masters, 1992). Though in these cases the definitions of equity and efficiency are slightly different, the philosophy and the dilemma between both concepts remain the same. Most of these authors highlight the importance of combining efficiency and equity in an integrated management of public resources and it is precisely this conflict what underpins the ideas developed in this article.

When quantitative risk analysis is applied to inform safety management of portfolios of dams, a high number of results are obtained. In this context, risk reduction indicators have proved to be a useful tool to prioritize risk reduction measures (Bowles, Parsons, Anderson, & Glover, 1999; Morales-Torres, Serrano-Lombillo, Escuder-Bueno, & Altarejos-García, 2016). Risk reduction indicators are numeric values obtained for each potential measure based on its costs and the risk reduction it provides and they are widely used to inform safety management in different fields (Lutter, Morrall, & Viscusi, 1999; Ramsberg & Sjöberg, 1997; Stewart & Mueller, 2008).

The present paper is based on the results of (Morales-Torres et al., 2016), published by the same authors. In the previous work, existing risk reduction indicators were reviewed and their utility was demonstrated, applying them to obtain prioritization sequences of measures in a real portfolio of dams. It was concluded that existing risk reduction indicators for critical infrastructures safety management are based on either equity or efficiency principles, but none of them combine both principles in a balanced way. For this reason, the work presented in the current study introduces a new risk reduction indicator called Equity Weighted Adjusted Cost per Statistical Life Saved (EWACSLS), which combines efficiency and equity principles.

In order to provide a proper background on the use of risk reduction indicators to obtain prioritization sequences of measures, section 2 summarizes the main findings of (Morales-Torres et al., 2016). Section 3 presents the structure and the advantages of the proposed indicator and section 4 explains the results obtained when applied to prioritize risk reduction measures in a real portfolio of dams.

2. EQUITY AND EFFICIENCY PRINCIPLES FOR RISK MANAGEMENT IN DAM SAFETY

As defined by (Kaplan, 1997), risk can be understood as the combination of three concepts: what can happen, how likely it is to happen, and what its consequences are. In the dam safety field, what can happen is the failure of the dam and the analyzed consequences are usually economic and social in nature. Different metrics and definitions have been developed to quantify risk. In general, three types of risk are usually defined in the literature (Jonkman, van Gelder, & Vrijling, 2003; Morales-Torres et al., 2016):

- **Individual risk:** Refers to the probability of harming the individual which is most at risk. Different definitions can be used to quantify this concept, in this paper it is defined as the probability that at least one person dies as a result of the dam's failure (SPANCOLD, 2012). Therefore, this risk is computed by multiplying the probability of failure of the dam by the probability that at least one person dies due to this failure. Individual risk is directly related with the equity principle, since the lower the individual risk, the higher the minimum level of protection provided to all the individuals. For this reason, according to (HSE, 2001), the application of this principle should prevail when individual risk is above the recommended value of tolerability.

- **Societal risk:** It is obtained by combining failure probabilities and the harmful consequences suffered by the population as a result of that failure, generally expressed in terms of loss of life. In the dam safety field, this risk is commonly represented by a single value obtained combining dam failure probability and the loss of life produced by this failure (Bowles, 2004; SPANCOLD, 2012; USACE, 2014). The societal efficiency principle is followed when the objective is lowering societal risk at low costs.

- **Economic risk:** Similarly to societal risk, economic risk is obtained by combining failure probability and the economic consequences of that failure (Bowles, 2004). The economic efficiency principle prioritizes alternatives with lower economic risk at lower costs. According to some authors (Bowles, 2001; HSE, 2001), this type of efficiency should only prevail when the infrastructure complies with tolerability recommendations.

Reducing individual risk is aligned with the equity principle whereas reducing economic and societal risks at the lowest costs is aligned with the efficiency principle. Therefore, when different risk reduction measures are prioritized, following different principles can lead to conflicts between "individual rights" and "societal benefits".

When a portfolio of dams is analyzed through quantitative risk analysis, many risk reduction measures must be evaluated and prioritized. As demonstrated in (Morales-Torres et al., 2016), risk reduction indicators can be a useful tool to obtain prioritization sequences of risk reduction measures, which can then be used as an input to inform portfolio safety management. The article laid out a procedure to obtain prioritization sequences based on risk reduction indicators. In each step of the sequence, the measure with the lowest value of the indicator was chosen. Of course, the obtained prioritization sequence depends on the risk reduction indicator used to define it. Hence, this procedure does not intend to choose between different alternatives but to prioritize them, assuming that with enough time and resources, all of them will be implemented.

In (Morales-Torres et al., 2016) existing risk reduction indicators to compare different investment alternatives are reviewed. This review comprises the dam safety field and other hazardous industries and the relation between risk reduction measures and equity and efficiency principles. In the dam safety field, two indicators are prevalent in the evaluation of risk reduction measures:

- **CSLS (Cost per Statistical Life Saved):** (ANCOLD, 2003; HSE, 2001) This indicator shows how much it costs to avoid each potential loss of life as a result of a dam failure. It is widely used to manage quantitative risk results in different fields (de Blaeij, Florax, Rietveld, & Verhoef, 2003; Khadam & Kaluarachchi, 2003; Lutter et al., 1999; Stewart & Mueller, 2008). Its value is obtained through the following formula:

$$CSLS = \frac{C_a}{r_s(base) - r_s(mea)} \quad (1)$$

Where $r_s(base)$ is the risk expressed in loss of lives for the base case, $r_s(mea)$ is the risk in lives after the implementation of the measure and C_a is the annualized cost of the measure including its annualized implementation costs, annual maintenance costs and potential changes in operation costs produced by the adoption of the measure.

CSLS compares costs with societal risk reduction, so when considering several measures, the measure with a minimal value of this indicator will be the one that employs the resources in a most efficient way. Therefore, this indicator is based on the principle of societal efficiency.

- **ACSLS (Adjusted Cost per Statistical Life Saved):** (ANCOLD, 2003; Bowles, 2001) This indicator has the same structure as CSLS but introduces an adjustment of the annualized cost to consider the economic risk reduction generated by the implementation of the measure. It is obtained with the following equation:

$$ACSLS = \frac{C_a - (r_e(base) - r_e(mea))}{r_s(base) - r_s(mea)} \quad (2)$$

Where $r_e(base)$ is the economic risk of the infrastructure for the base case and $r_e(mea)$ is the economic risk after the implementation of the measure. As in the previous case, it is based on the efficiency principle, though for adjusted costs, so it considers both societal and economic efficiency.

Other reviewed risk reduction indicators to prioritize risk reduction measures are:

- **CBR (Cost-Benefit Ratio):** Arises from the comparison of the costs of a measure with the economic risk reduction benefits resulting from its implementation. It follows the economic efficiency principle.
- **CSFP (Cost per Statistical Failure Prevented):** Expresses how much it costs to avoid infrastructure failure for each measure. Its formulation is based on failure probability, so it follows the equity principle.
- **ACSFP (Adjusted Cost per Statistical Failure Prevented):** Has the same form as CSFP but introduces an adjustment on the annualized cost to consider the reduction of economic risk produced by the implementation of the measure.
- **Individual Risk Decrease Index (IRDI):** Used to select whichever measure produces the highest decrease in individual risk in each step in the sequence regardless of other factors. This criterion is related to equity.
- **Societal Risk Decrease Index (SRDI):** As before but minimizing societal risk. This criterion is related to societal efficiency.
- **Economic Risk Decrease Index (ERDI):** As before but minimizing economic risk. This criterion is related to economic efficiency.

Each indicator is therefore either based on the efficiency or the equity principle, but none of them takes both principles into account. For this reason, it seems suitable to develop a new indicator that allows obtaining prioritization sequences of risk reduction measures combining both principles.

As explained in the previous paper, prioritization sequences can be represented in variation curves (Figure 1), which represent the variation of the aggregated risk in the portfolio as measures are implemented. In the X axis, annualized costs or implementation steps can be displayed while in the Y axis aggregated individual risk, societal risk or economic risk can be shown.

Depending on what is represented in each axis, the risk reduction indicator which will lead to the optimum sequence is different. The optimum sequence of the variation curve which represents aggregated societal risk versus costs will be the optimum from the societal efficiency point of view, since it represents the sequence which reduces societal risk at the lowest costs. For this reason this variation curve is called in this paper societal efficiency variation curve. Following the same logic, the graph showing individual risk versus costs is called equity variation graph and the graph showing economic risk versus costs is called economic efficiency variation graph.

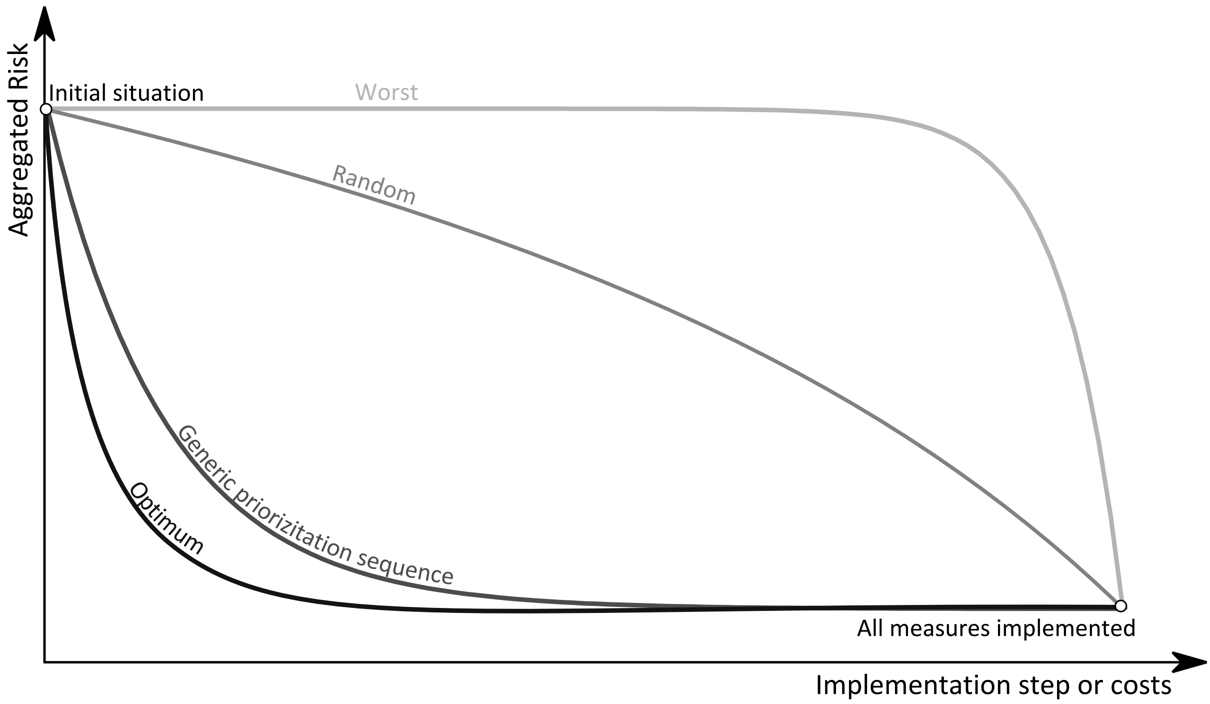

Figure 1. Generic representation of variation curves to define prioritization sequences.

In order to analyze how close prioritization sequences are to a risk reduction principle, three indexes based on variation curves were developed. These indexes are called CTB (closeness to the best) indexes and they are directly related to equity, societal efficiency and economic efficiency. For instance, in the equity variation graph, the prioritization sequences closer to the optimum will result in higher values of the CTB societal efficiency index. The same logic can be applied to equity and economic efficiency. These indexes allow evaluating any prioritization sequence of risk reduction measures against the general risk reduction principles.

3. EWACSLS: A RISK REDUCTION INDICATOR TO COMBINE EQUITY AND EFFICIENCY PRINCIPLES

As set out in the previous section, there is a need to find an indicator which can combine the principles of efficiency and effectiveness. We, therefore present here the Equity Weighted Adjusted Cost per Statistical Life Saved (EWACSLS), which is an indicator derived from ACSLS by introducing a correction to include the equity principle. EWACSLS is calculated with the following formula:

$$EWACSLS = \frac{ACSLS}{\left(\dfrac{\max(r_i(base), IRL)}{\max(r_i(mea), IRL)}\right)^n} \tag{3}$$

Where $r_i(base)$ is the individual risk for the base case expressed in years^{-1}, $r_i(mea)$ is the individual risk in years^{-1} after the implementation of the measure, *IRL* stands for Individual Risk Limit and *n* is a parameter that allows assigning a higher weight to either efficiency or equity in the prioritization process. The EWACSLS indicator has economic units, as ACSLS does. As can be derived from the previous formula, if the individual risk is lower than IRL, the only prevailing principle is efficiency (through ACSLS), since the denominator of the formula is then 1. Therefore, the equity principle only modifies the value of the indicator in the cases where individual risk is above tolerability thresholds. In this sense, it follows the HSE recommendations for risk management, combining equity and efficiency for non-tolerable risks and taking only efficiency into account in the tolerable area.

Consequently, the Individual Risk Limit indicates the level of protection to be provided to all the individuals in order to satisfy the equity principle. This limit cannot be prescribed in this article in a general way which could be blindly applied to all infrastructures. Its level is linked to implications on values which are subjective and which can vary from one organization or country to another and it is therefore part of the wider risk tolerability framework which should underlie any risk management effort. The formula itself, however, is flexible enough to accommodate these differences. In dam safety, an IRL of 10^{-4} years^{-1} can be a sensible choice in many cases, following recommendations on risk tolerability which are widely used in the field (USACE, 2014).

The *n* parameter can be used to provide flexibility to the EWACSLS. If the value of *n* is very high, the prevailing prioritization principle is equity whereas if it is very low, efficiency prevails. Hence, once a value of *n* is set, it can be used to consistently compare an array of measures. A value of *n* equal to 1 seems to be a reasonable compromise between both principles, as shown in Table 1. This table has been elaborated based on the authors' practical experience, after having used this risk reduction indicator to inform dam safety management in more than 35 dams worldwide. The effect of this parameter in the prioritization sequences of a real case is analyzed in the following section.

n parameter	Predominant risk reduction principle when r_i > IRL
1/10	Societal and economic efficiency clearly prevailing
1/2	Efficiency slightly more significant than equity
1	Equilibrium between equity and efficiency
2	Equity slightly more significant than efficiency
10	Equity clearly prevailing

Table 1. Recommended values for the n parameter of the EWACSLS indicator.

Summarizing, the EWACSLS indicator incorporates equity, societal efficiency and economic efficiency principles. Figure 1 uses a Venn diagram to visualize the relationship between all the reviewed indicators and principles. As can be observed in this figure, EWACSLS is the only indicator that is related with the three risk reduction principles.

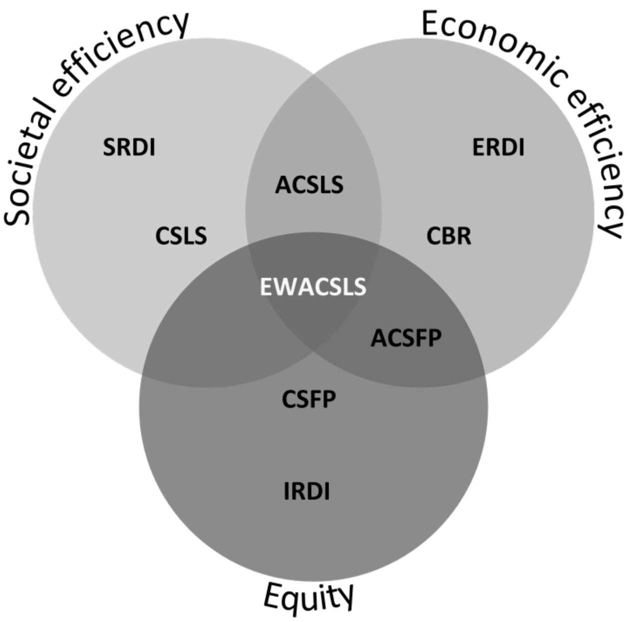

Figure 2. EWACSLS in a Venn diagram that shows the relationship between risk reduction indicators and efficiency and equity principles.

The EWACSLS indicator allows a smooth transition between equity and efficiency principles, since the closer the individual risk is to its limit, the less weight the equity principle has. This indicator is better aligned with risk analysis principles than simply establishing a binary threshold determining whether equity should prevail or not. If this kind of binary threshold is used, only equity is taken into consideration in the non-tolerable area and only efficiency in the tolerable area, so principles are used in separated domains. The results of this approach would be more sensible to existing uncertainties in risk estimation, since small changes in individual risk could produce changes in the prevailing principles. Risk evaluation and governance should not be about being above or under a threshold, but about informing decision making combining both principles in order to reduce risk as much as possible.

4. CASE STUDY: A PORTFOLIO OF 27 DAMS IN SPAIN

In order to compare the results of EWACSLS with the other risk reduction indicators, the same case study as in (Morales-Torres et al., 2016) has been used. EWACSLS has been applied to prioritize safety investments in a real portfolio of 27 dams in Spain. These dams belong to the same owner, which has defined a list of 93 safety measures to be implemented in the dams in the following years. It is a very heterogeneous portfolio of dams including structures of different typology as can be observed in Table 2. .

Tipologies	
Concrete gravity dams	15
Small diversion dams	4
Embankments	3
Double-curve arch dams	3
Single-curve arch dams	2
TOTAL	27
Maximum height (m)	11.6 - 100.6
Reservoir volume (m^3)	0.2 - 641
Construction year	1923 - Under construction

Table 2. General data of the dams in the Portfolio.

During four years, a risk analysis process was completed in this set of dams to develop quantitative risk models in order to inform dam safety management. In this process, numerous professionals related with the dams operation and management participated in the working sessions to define the potential failure modes and the architecture and inputs of the risk models. The quantitative risk results obtained from this process are the starting point of this case study, which is focused on how to manage these results using the EWACSLS indicator.

In this risk analysis process, a quantitative risk model was set up for each dam using iPresas software (iPresas, 2014). An example of these models is shown in Figure 3. These risk models are based on event trees (SPANCOLD, 2012) and they analyze the different ways in which a dam can fail (failure modes) resulting from a loading event, calculating their probabilities, consequences and risks. Input data in the risk models were elaborated during the risk analysis process and are the result of existing technical documents (safety reviews, emergency action plans, operating rules, construction projects…), numerical models and working group sessions. Risk models were elaborated for normal and hydrological loading scenarios and include probability of flood events, water pool levels and outlets availability, flood routing results, fragility curves for each failure mode and expected consequences of failure (loss of life and economic damages). Detailed procedures followed to develop these risk models can be found in (Altarejos-García, Escuder-Bueno, Serrano-Lombillo, & Morales-Torres, 2012; Ardiles et al., 2011; Serrano-Lombillo, Escuder-Bueno, de Membrillera-Ortuño, & Altarejos-García, 2011; Serrano-Lombillo, Fluixá-Sanmartín, & Espert-Canet, 2012; Serrano-Lombillo, Morales-Torres, & García-Kabbabe, 2012).

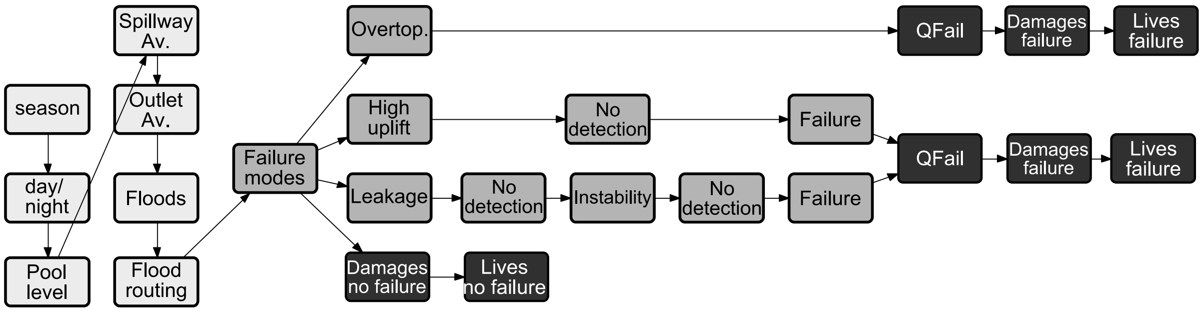

Figure 3. Quantitative risk model of one of the case study dams.

The 93 measures planned to improve dams safety include 38 structural measures and 55 non-structural measures. Proposed measures are not general measures for all the dams: each of them is planned and tailored to be applied only in one dam. Some examples of the planned structural measures are increment of spillway capacity or improvements in the gates reliability, the foundation conditions or the dam body imperviousness. The non- structural measures are mainly focused on developing Emergency Action Plans and risk awareness campaigns, improving the monitoring systems and introducing more restrictive freeboards in the reservoirs.

Following Spanish recommendations on hydraulic infrastructures management (MMARM, 2001), the implementation cost of each measure was annualized by distributing it along its lifespan with a discount rate of 5%. Then, the annual maintenance and operation costs were added to the annualized implementation cost. In this way, the total cost of every measure was expressed in monetary units (in this case, euros) per year.

In this case study, individual risk was assumed to be equal to the failure probability of the dams. This is a common hypothesis in large dams (USBR, 2011) as the ones studied in this case, since dam failure would almost certainly result in at least one fatality. Risk models were used to quantify the risk reduction provided by each measure planned. Therefore, these results were combined with the annualized cost to compute EWACSLS. The limit of individual risk (IRL) used to calculate EWACSLS was 10^{-4}, following USACE recommendations (USACE, 2014).

Incremental risk results have been used to compute risk reduction indicators. Incremental risk is the part of risk usually used to inform dam safety management (ANCOLD, 2003; SPANCOLD, 2012; USACE, 2014), since it is exclusively due to the dam failure. It is obtained by subtracting from the consequences of the dam failure the ones that would have happened even if the dam had not failed.

Before presenting the results for the full case and with the aim of clarifying the prioritization process with the EWACSLS indicator, a first sequence is shown below using only 3 dams of the Portfolio and 9 of their potential risk reduction measures. This sequence is obtained with a value of the *n* parameter equal to 1. The procedure to obtain the prioritization sequence can be observed in Table 3. In each step, EWACSLS is computed for each measure based on its cost and the risk results for the initial situation and the situation with the measure implemented. Then, the measure with the lowest value of the EWACSLS indicators is chosen. In the next step of the sequence, the initial situation will assume that the measures of the previous steps have already been implemented, so risk reduction provided by each measure and EWACSLS are recomputed to choose a new measure. Finally, when the whole sequence has been defined, aggregated risks can be represented versus annualized costs in each step to obtain the variation graphs.

Dam	Measure	Annualized cost (M€/year)	Initial situation			Situation with measure			EWACSLS (M€/live)
			Individual risk (years^{-1})	Economic risk (M€/year)	Societal risk (lives/year)	Individual risk (years^{-1})	Economic risk (M€/year)	Societal risk (lives/year)	
			CURRENT SITUATION						
A	Emergency action plan	4.768E-02	1.958E-05	1.457E-03	2.975E-03	1.958E-05	1.457E-03	1.463E-03	31.54
A	Parapet wall reinforcement	4.728E-03				6.452E-08	4.893E-06	1.014E-05	**1.10**
A	New bottom outlet	1.122E-02				1.614E-05	1.201E-03	2.450E-03	20.88
A	New gates in spillway	2.738E-02				1.375E-05	1.023E-03	2.082E-03	30.17
B	Emergency action plan	7.984E-02	7.645E-07	6.873E-04	8.771E-04	7.645E-07	6.873E-04	3.484E-04	151.01
B	Monitoring improvement	3.910E-03				4.196E-07	3.905E-04	5.190E-04	10.09
B	New power generator	2.597E-03				5.891E-07	5.218E-04	6.547E-04	10.93
C	Emergency action plan	9.847E-02	5.582E-04	3.231E-03	6.815E-04	5.582E-04	3.231E-03	4.407E-04	409.05
C	Saddle dam reinforcement	1.507E-01				3.613E-07	1.193E-04	5.327E-04	177.78
			STEP 1: DAM A - PARAPET WALL REINFORCEMENT						
A	Emergency action plan	4.768E-02	6.452E-08	4.893E-06	1.014E-05	6.452E-08	4.893E-06	4.970E-06	9224.08
A	New bottom outlet	1.122E-02				3.882E-08	2.944E-06	6.105E-06	2780.15
A	New gates in spillway	2.738E-02				6.056E-09	4.592E-07	9.506E-07	2978.95
B	Emergency action plan	7.984E-02	7.645E-07	6.873E-04	8.771E-04	7.645E-07	6.873E-04	3.484E-04	151.01
B	Monitoring improvement	3.910E-03				4.196E-07	3.905E-04	5.190E-04	**10.09**
B	New power generator	2.597E-03				5.891E-07	5.218E-04	6.547E-04	10.93
C	Emergency action plan	9.847E-02	5.582E-04	3.231E-03	6.815E-04	5.582E-04	3.231E-03	4.407E-04	409.05
C	Saddle dam reinforcement	1.507E-01				3.613E-07	1.193E-04	5.327E-04	177.78
			STEP 2: DAM B - MONITORING IMPROVEMENT						
A	Emergency action plan	4.768E-02	6.452E-08	4.893E-06	1.014E-05	6.452E-08	4.893E-06	4.970E-06	9224.08
A	New bottom outlet	1.122E-02				3.882E-08	2.944E-06	6.105E-06	2780.15
A	New gates in spillway	2.738E-02				6.056E-09	4.592E-07	9.506E-07	2978.95
B	Emergency action plan	7.984E-02	4.196E-07	3.905E-04	5.190E-04	4.196E-07	3.905E-04	2.097E-04	258.13
B	New power generator	2.597E-03				2.444E-07	2.253E-04	2.969E-04	**10.95**
C	Emergency action plan	9.847E-02	5.582E-04	3.231E-03	6.815E-04	5.582E-04	3.231E-03	4.407E-04	409.05
C	Saddle dam reinforcement	1.507E-01				3.613E-07	1.193E-04	5.327E-04	177.78
			STEP 3: DAM B - NEW POWER GENERATOR						
A	Emergency action plan	4.768E-02	6.452E-08	4.893E-06	1.014E-05	6.452E-08	4.893E-06	4.970E-06	9224.08
A	New bottom outlet	1.122E-02				3.882E-08	2.944E-06	6.105E-06	2780.15
A	New gates in spillway	2.738E-02				6.056E-09	4.592E-07	9.506E-07	2978.95
B	Emergency action plan	7.984E-02	2.444E-07	2.253E-04	2.969E-04	2.444E-07	2.253E-04	1.196E-04	450.44
C	Emergency action plan	9.847E-02	5.582E-04	3.231E-03	6.815E-04	5.582E-04	3.231E-03	4.407E-04	409.05
C	Saddle dam reinforcement	1.507E-01				3.613E-07	1.193E-04	5.327E-04	**177.78**
			STEP 4: DAM C - SADDLE DAM REINFORCEMENT						
A	Emergency action plan	4.768E-02	6.452E-08	4.893E-06	1.014E-05	6.452E-08	4.893E-06	4.970E-06	9224.08
A	New bottom outlet	1.122E-02				3.882E-08	2.944E-06	6.105E-06	2780.15
A	New gates in spillway	2.738E-02				6.056E-09	4.592E-07	9.506E-07	2978.95
B	Emergency action plan	7.984E-02	2.444E-07	2.253E-04	2.969E-04	2.444E-07	2.253E-04	1.196E-04	**450.44**
C	Emergency action plan	9.847E-02	3.613E-07	1.193E-04	5.327E-04	3.613E-07	1.193E-04	3.147E-04	451.60
			STEP 5: DAM B - EMERGENCY ACTION PLAN						
A	Emergency action plan	4.768E-02	6.452E-08	4.893E-06	1.014E-05	6.452E-08	4.893E-06	4.970E-06	9224.08
A	New bottom outlet	1.122E-02				3.882E-08	2.944E-06	6.105E-06	2780.15
A	New gates in spillway	2.738E-02				6.056E-09	4.592E-07	9.506E-07	2978.95
C	Emergency action plan	9.847E-02	3.613E-07	1.193E-04	5.327E-04	3.613E-07	1.193E-04	3.147E-04	**451.60**
			STEP 6: DAM C - EMERGENCY ACTION PLAN						
A	Emergency action plan	4.768E-02	6.452E-08	4.893E-06	1.014E-05	6.452E-08	4.893E-06	4.970E-06	9224.08
A	New bottom outlet	1.122E-02				3.882E-08	2.944E-06	6.105E-06	**2780.15**
A	New gates in spillway	2.738E-02				6.056E-09	4.592E-07	9.506E-07	2978.95
			STEP 7: DAM A - NEW BOTTOM OUTLET						
A	Emergency action plan	4.768E-02	3.882E-08	2.944E-06	6.105E-06	3.882E-08	2.944E-06	2.992E-06	15317.54
A	New gates in spillway	2.738E-02				2.465E-09	1.869E-07	3.868E-07	**4787.06**
			STEP 8: DAM A - NEW GATES IN SPILLWAY						
A	Emergency action plan	4.768E-02	2.465E-09	1.869E-07	3.868E-07	2.465E-09	1.869E-07	1.897E-07	**241848.36**
			STEP 9: DAM A - EMERGENCY ACTION PLAN						

Table 3. Detailed process to obtain a prioritization sequence for 3 dams and 9 measures.

The same process described above as an example for 3 dams was applied to the full case with 27 dams and 93 risk reduction measures, resulting in a more numerically complex calculation, where each step of the sequence requires a large amount of computations. The process, however, remains the same. Below, we discuss the results obtained.

The high number of risk reduction measures to be prioritized justifies the use of risk reduction indicators to define these sequences more efficiently, since there are $93! \approx 10^{144}$ possible sequences of measures to be considered. In order to illustrate it, a sequence corresponding to a random average case has been calculated to compare with the implementation sequences obtained from the application of the risk reduction indicators. In order to obtain this average, 1,000 random sequences have been obtained, choosing the measure randomly in each step. The random average case has been then determined by obtaining the average risk variation of all of them for each implementation step. Figure 4 compares these sequences with the sequence obtained choosing in each step the measure with a lower value of the EWACSLS indicator. As can be observed, the sequence obtained with EWACSLS performs much better than any of the random sequences, since it reduces risks with lower costs. It should be remarked that the Optimum sequence shown in Figure 4 is only the best for this type of variation graph (with the societal risk represented in the Y axis and annualized cost in the X axis) since no sequence of measures that is optimum for all the types of variation graphs and principles exists. In this variation graph, this sequence is obtained using the CSLS indicator.

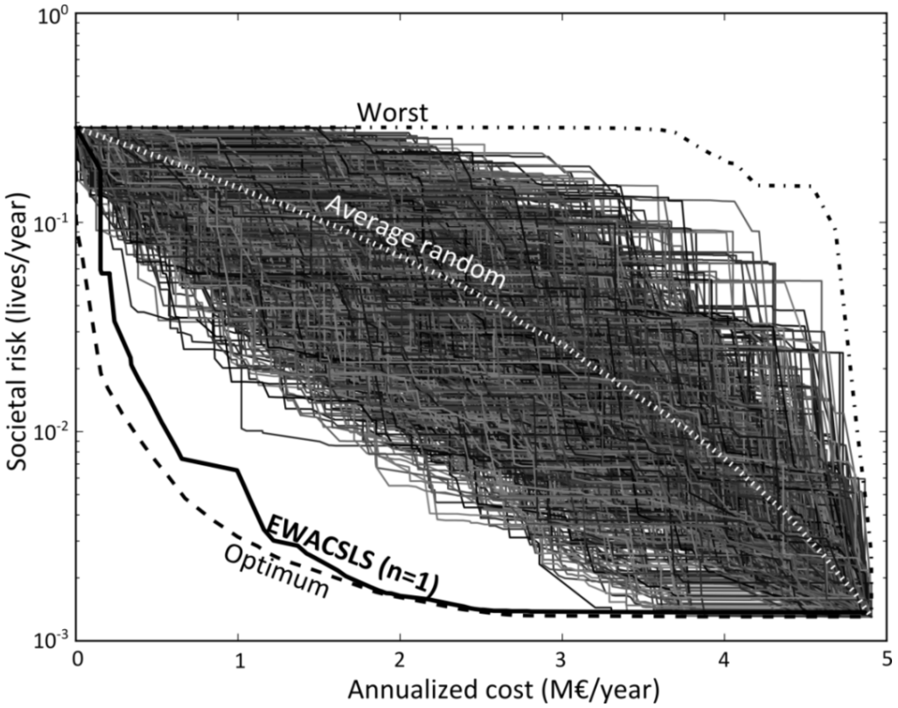

Figure 4. Comparison of the results of the 1000 randomly calculated cases with the sequence obtained with EWACSLS indicator in the societal efficiency variation curve.

In order to analyze in detail the results obtained through the use of the indicator proposed in this article, EWACSLS, several implementation sequences were obtained for different values of the *n* parameter: 20, 5, 2, 1, 0.5, 0.2 and 0.05. Figure 5 shows implementation sequences for different *n* values in the equity, societal efficiency and economic efficiency variation curves. It should be remarked that in each variation curve, optimum sequences have been obtained with a different indicator (CSFP, CSLS and ECBR respectively), since no sequence that is optimum for the three of them exists.

Table 4 shows how CTB indexes vary for different values of the n parameter. In this table, EWACSLS CTB values are compared with the results of the sequences produced by the other risk reduction indicators. The result labelled as "ACSFP/ACSLS" represents a sequence obtained combining these two indicators: ACSFP (with failure probabilities higher than 10^{-4}) and ACSLS (with failure probabilities lower than 10^{-4}). As can be observed in these results, EWACSLS, is not the optimum in any of the ratios, but has a very good score in all of them, being the most balanced of all of the indicators under study. Differences between the sequences obtained with ACSLS and EWACSLS are due to measures which are not so valuable from a pure efficiency point of view but are more justified from an equity point of view.

As can be observed in Table 4 and in Figure 6, higher *n* values produce better results of equity index, whereas lower values prioritize societal efficiency. Economic efficiency increases slightly with n, due to two opposed effects: if the value of *n* is lower, ACSLS is more important in the prioritization and has to take into account economic efficiency since it uses adjusted costs. If the value of *n* is higher, equity prevails, which also produces good economic efficiency in this specific case study, since none of the introduced measures directly diminishes economic consequences and that failure probability reductions produce a similar change of economic risk. In every case, the values of economic efficiency CTB are very good independently of the value of *n*.

In order to compare graphically how efficiency and equity principles are combined according to the value of parameter n, the CTB indexes obtained for both principles have been represented in Figures 7 and 8. These figures strengthen the notion that EWACSLS is a good criterion of measure prioritization since it combines evenly the principles of societal and economic efficiency with equity, obtaining values of their three CTB close to one.

Furthermore, with EWACSLS it is possible to vary a measure implementation sequence giving more or less relative weight to the principles of efficiency or equity thanks to parameter *n*, while still obtaining values of CTB indexes that are close to the optimal ones. As can be seen in Figures 7 and 8, the dotted line of EWACSLS varies between ACSLS ($n = 0$) and the ACSFP/ACSLS combination ($n \to \infty$), which is a logical consequence of its mathematical formulation. Finally, this indicator allows the introduction of a two-step-like process in an implicit way, since it only considers the equity principle when dam failure probability is over the IRL (10^{-4} in this case).

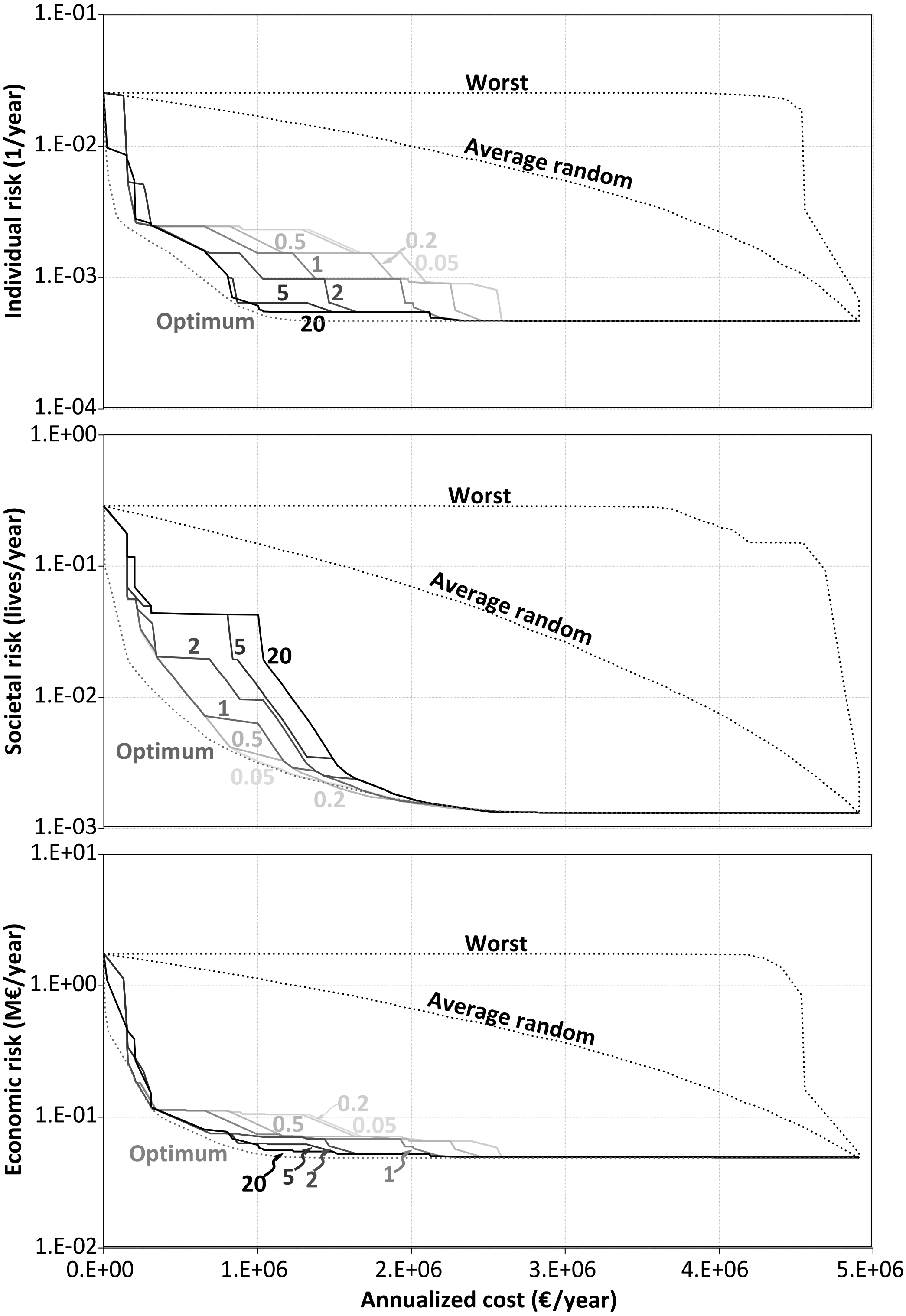

Figure 5. Implementation sequences for different n values in the variation curves of equity, societal efficiency and economic efficiency.

Indicator		Economic efficiency CTB	Societal efficiency CTB	Equity CTB
EWACSLS	**n=0.05**	87.9%	87.5%	79.8%
	n=0.1	87.9%	87.5%	79.9%
	n=0.2	88.0%	87.5%	79.9%
	n=0.33	89.1%	87.5%	81.8%
	n=0.5	89.3%	87.4%	82.2%
	n=0.75	89.7%	87.2%	84.0%
	n=1	90.2%	86.6%	84.7%
	n=1.5	91.4%	85.1%	86.3%
	n=2	91.8%	84.3%	87.7%
	n=3	91.7%	82.8%	88.1%
	n=5	92.0%	81.9%	89.2%
	n=10	92.6%	80.8%	90.3%
	n=20	92.5%	80.1%	90.5%
CSLS		81.2%	**90.0%**	73.1%
ACSLS		87.7%	87.5%	79.0%
ECBR		**94.6%**	62.0%	91.6%
IRDI		86.9%	56.1%	89.4%
SRDI		71.8%	83.9%	59.1%
ERDI		90.5%	57.6%	88.6%
CSFP		91.7%	55.3%	**93.5%**
ACSFP		92.7%	55.3%	92.2%
ACSFP/ACSLS		92.1%	79.5%	91.1%
BCA		82.7%	72.5%	71.3%
Random average		38.2%	38.3%	34.4%
Worst societal ef.		5.6%	**3.6%**	9.8%
Worst economic ef.		**5.2%**	37.2%	4.2%
Worst equity		5.5%	36.3%	**4.0%**

Table 4. CTB indexes for EWACSLS (with different values of the n parameter) and the others risk indicators. Results in boldface show the highest and lowest values for each CTB index.

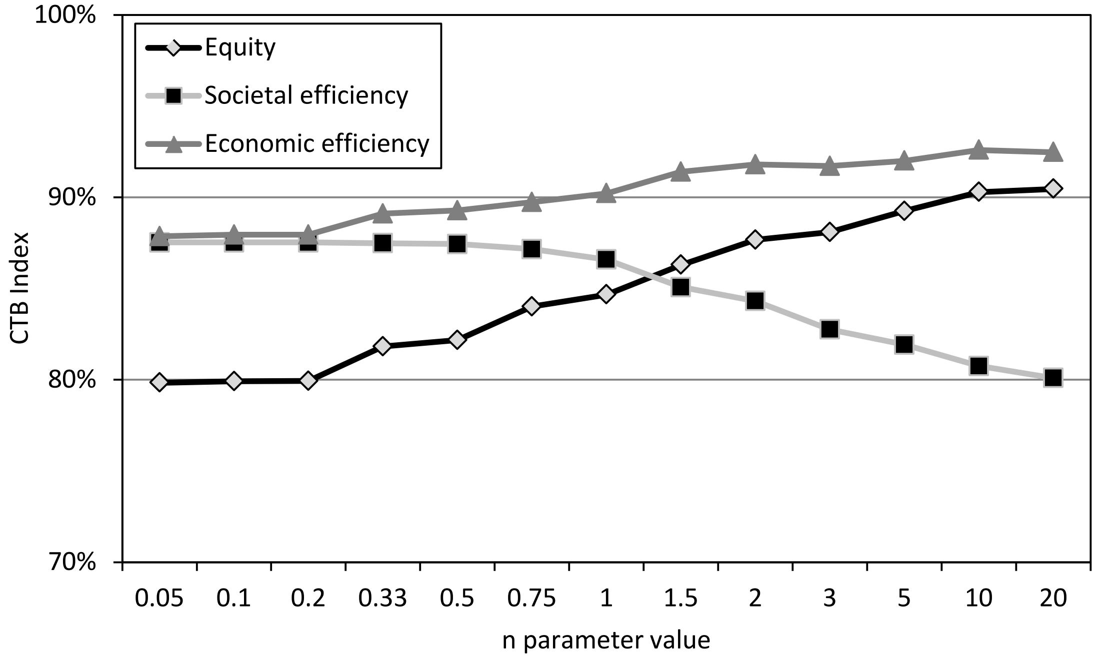

Figure 6. CTB variation for EWACSLS with different values of the parameter n.

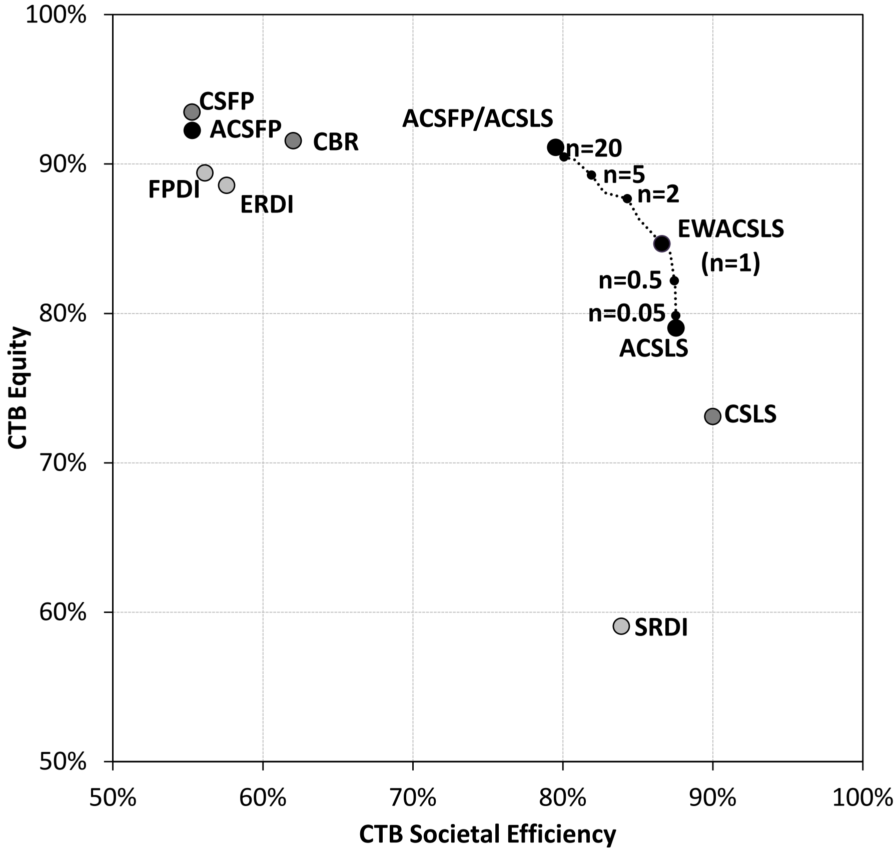

Figure 7. Comparison between societal efficiency CTB and equity CTB for EWACSLS and the other risk indicators.

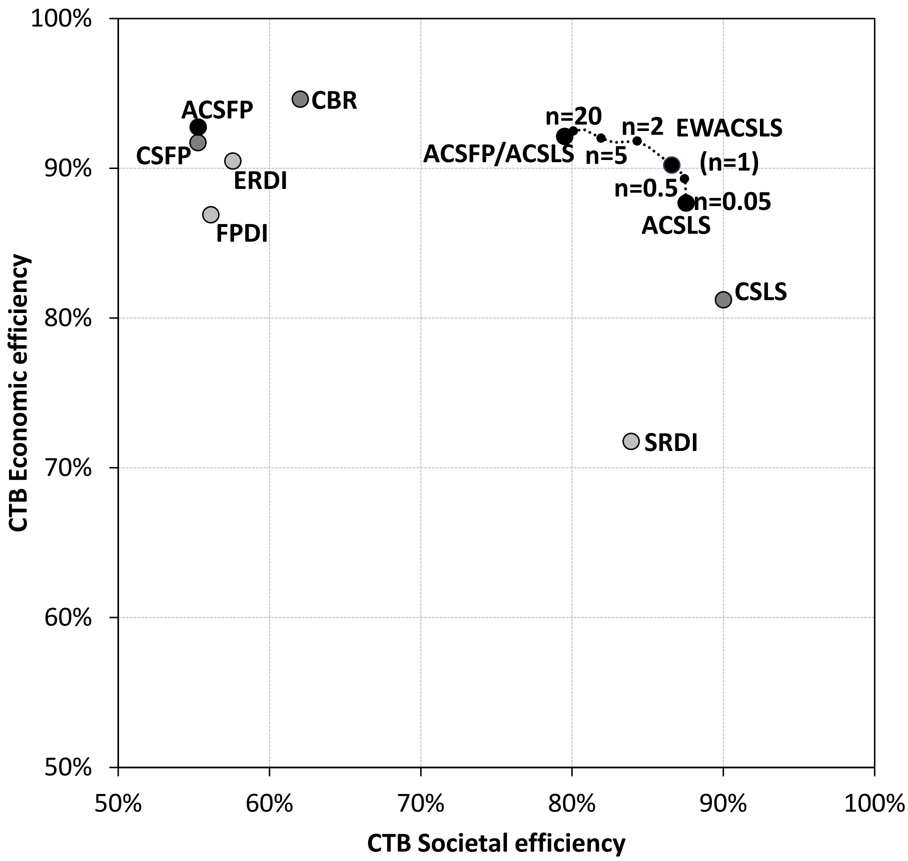

Figure 8. Comparison between societal efficiency CTB and economic efficiency CTB for EWACSLS and the other risk indicators.

5. DISCUSSION AND CONCLUSIONS

Governance of critical infrastructures safety is a complex process, where techniques, people, policies, resources, social norms, and information interact. For this reason, not only technical but also economic, social and political issues play a significant role. Quantitative risk analysis has proved to be a suitable methodology to inform dam safety management, since it provides a clear identification of the risks and of the effects of risk reduction measures.

In this context, risk reduction indicators are a useful tool to manage quantitative risk results since they allow risk managers to obtain prioritization sequences of very different structural and non-structural measures in a clear and justifiable way. These sequences should not be taken as a prescription but as a valuable input to decision-making and can be an input to a more global multi criteria analysis in order to combine them with other economic, social, psychological and political considerations.

Sound risk management is based on the efficiency and equity principles. Whereas equity is related to providing a certain level of protection to everybody, efficiency is related to reducing risks at the lowest costs. In many cases, these principles can conflict, producing different prioritizations of risk reduction measures. This conflict between equity and efficiency principles is the underlying motive of this article, as existing risk indicators are either based on the equity or efficiency principles but cannot accommodate both at the same time.

The Equity Weighted Adjusted Cost per Statistical Life Saved (EWACSLS) indicator presented in the article enables to obtain a prioritized sequence that balances efficiency and equity while offering good results for both principles. Moreover, the indicator has been formulated in a flexible way, such that by changing one parameter (n), more or less relative weight can be granted to efficiency or equity. These advantages make EWACSLS an excellent indicator for real-world use in risk management decision making which smoothly blends efficiency and equity considerations.

The utility of this indicator has been proved in a real case study of 27 dams with 93 potential risk reduction measures to be prioritized. The sequence obtained with EWACSLS has been compared with sequences obtained with other existing risk reduction indicators. Results show that EWACSLS is not the best from any single perspective, but has very good results from all of them, being the most balanced of all of the compared indicators.

This paper is mainly focused on risk analysis to inform dam safety management, but the EWACSLS indicator can also be used in other fields in order to analyze quantitative risk results for safety management. The concepts and the dilemma behind this indicator are equally appropriate for other critical infrastructures, since combining equity and efficiency principles is of vital importance for a balanced and integrated risk management.

In real cases, the prevailing principle will depend on the preferences, values and legal restrictions of each country and owner. In any case, comparing and combining both principles in a flexible way will be very interesting for managers, especially in the public sector, where equity and efficiency principles have traditionally produced more conflicts.

6. ACKNOWLEDGEMENTS

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Annex 4

Building Fragility Curves of Sliding Failure of Concrete Gravity Dams Integrating Natural and Epistemic Uncertainties

Authors: Adrián Morales-Torres, Ignacio Escuder-Bueno, Luis Altarejos-García, and Armando Serrano-Lombillo.

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Building fragility curves of sliding failure of concrete gravity dams integrating natural and epistemic uncertainties

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Abstract

In the majority of engineering problems, two kinds of uncertainty are generally considered: natural uncertainty, resulting from the inherent variability in natural processes, and epistemic uncertainty, linked to lack of knowledge. When performing a quantitative risk analysis, considering both types of uncertainty separately before integrating them when performing risk calculations, allows a better understanding on how both types of uncertainty influence risk results.

The main purpose of this paper is presenting a consistent procedure to perform fragility analysis for dams in order to identify and track natural and epistemic uncertainty separately. This procedure is particularized for the sliding failure mode of concrete gravity dams, due to its importance. The resulting fragility curves provides a valuable input to quantitative risk models in order to compare the effect of risk reduction and uncertainty reduction investments.

The proposed procedure combines the concepts of the Electrical Power

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Research Institute (EPRI) guidelines to develop fragility curves for the nuclear industry with existing reliability techniques for computing fragility curves in the context of concrete dams engineering. The procedure has been applied to a dam to illustrate how it can be used in a real case in such a manner that fragility curves are obtained integrating natural and epistemic uncertainties without losing track of their separate contribution to risk results.

Keywords: Fragility analysis, Concrete dams, Sliding failure mode, Natural and epistemic uncertainty, Quantitative risk analysis

1. Introduction

Engineering tools such as risk analysis can be useful to inform decisions regarding dam safety governance [1]. Risk assessment tools and techniques are routinely used by several industries [2, 3, 4, 5, 6]. Benefits from the risk analysis approach are recognized even when limited data are available as risk assessment helps engineers to understand uncertainties in a project, and provides a logical process of identifying hazards, evaluate the severity of each hazard, and assess the effectiveness of risk reduction measures [7].

However, the contextual information provided above is way more complex than it may sound, veiling lots of theoretical and practical difficulties. Many of these difficulties are related to how uncertainties are explicitly considered today (in the context of risk analysis), in contrast to the more traditional implicit treatment (in the context of state-of-the-art dam safety practice).

With regard to uncertainties present in the analysis of the future behavior of a constructed facility, whose analysis should play an important role in the dam safety evaluation, many authors have identified two distinctive categories or sources [8, 9, 10, 11, 4] as shown in figure 1:

- **Natural uncertainty or randomness:** produced by the inherent variability in the natural processes. It includes the variability along time of phenomena that take place in a precise point of the space (temporal variability) or the variability across the space of phenomena that take place in different points but simultaneously (spatial variability).

  An example of this kind of uncertainty is the variability of the loads that the structure has to withstand, for instance, the variability in the potential intensity of earthquakes. Another example is the strength's variability of the foundation where the structure stands. This type of uncertainty, sometimes also called aleatoric uncertainty, cannot be reduced, though it can be estimated.

- **Epistemic uncertainty:** resulting from lack of knowledge or information about the analyzed system. This uncertainty can be divided in two categories: uncertainty of the model and uncertainty of the parameters. The uncertainty of the model refers to the ignorance of the extent to which a model reproduces reality faithfully. It reflects the incapacity of representing reality or of identifying the best model to do it. The uncertainty in the parameters arises from the restricted capacity to estimate them in an adequate manner from a limited number of data from tests or calibration, including measurement errors (related to the meter or the operator), survey error and also from the inherent limitations of the statistical techniques used in the estimation of the parameters. The more knowledge is available about a structure, the more this type of uncertainty can be reduced. On the other hand, it is usually very difficult to estimate or quantify this uncertainty.

  An example of this type of uncertainty can also be found in the strength of the foundation. The information about the foundations may be limited so the parameters used to characterize its resistance are estimated though probing and exploration. With more resources, the foundation can be better characterized and the epistemic uncertainty is reduced, although the natural variability of the foundation may still be very significant.

The distinction between natural and epistemic uncertainty takes added importance for a quantitative risk analysis in complex structures [12]. In this context, natural uncertainty is usually related to the occurrence of events that can produce the structural failure and the randomness of the structure's resistant behavior for the load produced by the events. In contrast, epistemic uncertainty is mainly focused on the lack of knowledge of the loading events, the failure mechanisms, the structure's resistance parameters and the consequences produced by the failure.

Uncertainties in dam safety have been treated in detail by several authors [13, 10, 14], and discussions include not only parameter and system uncertainty, but also loading uncertainty. Several studies have tried to distinguish

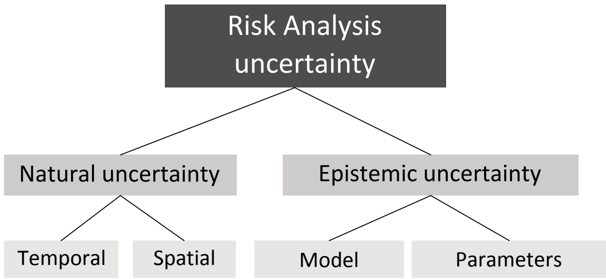

Figure 1: Taxonomy of uncertainty in Risk Analysis (adapted from [10]).

between both types of uncertainty in the dam safety field [15, 16]. In particular, [17] makes a detailed review of epistemic and natural uncertainties for the sliding failure mode of concrete dams.

As explained by Paté-Cornell [18], different levels of risk analysis complexity can be achieved depending on how uncertainty is addressed. In the dam safety field, quantitative risk analysis is commonly addressed defining different failure mechanisms for failure events [4, 19, 20]. In general, a single value of failure probability and risk is estimated for each failure mechanism combining both types of uncertainty.

Other industries like nuclear and aeronautical have achieved a higher level of complexity, with a second-order probabilistic risk analysis based on a full representation and separation of epistemic and natural uncertainty [18]. In this case, a failure probability and risk profile is obtained to represent the influence of epistemic uncertainty in the results. With this approach, the effect of measures for epistemic uncertainty reduction can also be evaluated and compared with risk reduction measures favoring a better informed dam safety management. Altarejos [21] had also suggested a procedure for slopes and embankment dams.

In this paper, the authors present a procedure to adapt the methodology developed in the nuclear industry to the dam safety field. This procedure develops fragility analysis, which accounts for both types of uncertainty. This paper is focused on applying this procedure for the sliding failure mode of concrete gravity dams, although it can be used for fragility analysis of other structural failure modes. The present paper has a broad scope since it is focused on the presented procedure to develop this fragility analysis rather than on reviewing how considering aleatory and epistemic uncertainty in specific parameters and equations of the existing numerical models for the sliding failure in concrete dams.

Sliding failure mode has been selected since sliding produced by insufficient shear strength in the foundation is the most common cause of failure of concrete gravity dams according to the International Commission on Large Dams [22]. For this reason, regulatory rules and guidelines in most countries addresses this failure mode and, indeed, it has been recently analyzed with mathematical models and reliability techniques by different authors [23].

The procedure, after being presented, is later is applied to a concrete gravity dam in Spain in order to illustrate how a fragility analysis can be performed and integrated into a risk calculation model to characterize probability of failure and risk in a more comprehensive way.

2. Fragility analysis and uncertainty

In the risk analysis context, fragility curves represent a relationship between conditional failure probability and the magnitude of loads that produce failure. Risk is the combination of three concepts: what can happen, how likely is it to happen, and what are its consequences [24]. Following this definition, one possible way to quantify risk is with the following equation [25]:

$$Risk = \int P(loads) \cdot P(response|loads) \cdot C(loads, response) \tag{1}$$

Where the integral is defined over all the events under study, *P(loads)* is the probability of the different load events, *P(response|loads)* is the conditional probability of the structural response for each load event and *C(loads, response)* are the consequences of the system response for each load event.

According to this equation, fragility curves address the second term of the equation, providing the conditional failure probability of the structure for a range of loading events. An example for the sliding failure mode of a gravity dam is shown in Figure 2, where the loading state is represented by the water level in the reservoir.

Therefore, fragility curves provide a representation of the uncertainty about the structural response for a load event. Without uncertainty, the structural response (failure or not) for each loading event would be deterministic.

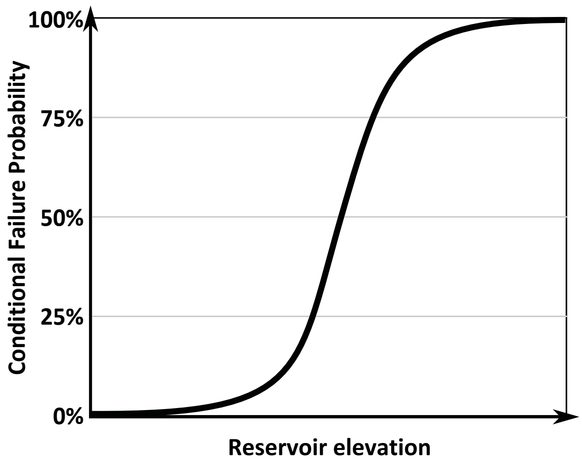

Figure 2: Example of fragility curve for the sliding failure mode.

Different empirical and analytical methodologies have been developed to obtain fragility curves in complex structures [26, 27]. In general, these curves are calculated with reliability analysis techniques, which estimate the probability of the load effect exceeding the resistance effects of the structure. This estimation is made evaluating the uncertainty of the input variables in the structural analysis.

When a single fragility curve is obtained to characterize the system's response, it usually addresses both types of uncertainty: epistemic and natural. Hence, when reliability techniques are applied to obtain a fragility curve, these two types of uncertainty are usually analyzed together in the input variables [13].

In order to separate both types of uncertainty, Kennedy & Ravindra defined a conceptual framework [28] that was used by EPRI to develop a methodology for risk-informed safety management in the nuclear industry [26]. According to this methodology, the system response for a loading state (i.e. an earthquake event) can be defined by a family of fragility curves instead of a single curve, as shown in Figure 3.

In this methodology, fragility curves are described by log-normal distributions, defined by parameters for the aleatory uncertainty: m_R (median or logarithmic mean) and β_R (logarithmic standard deviation). Epistemic uncertainty is modeled by treating the logarithmic mean as a Bayesian random variable, M_R, with median m_R and log-std dev β_U. Thus, in the family of

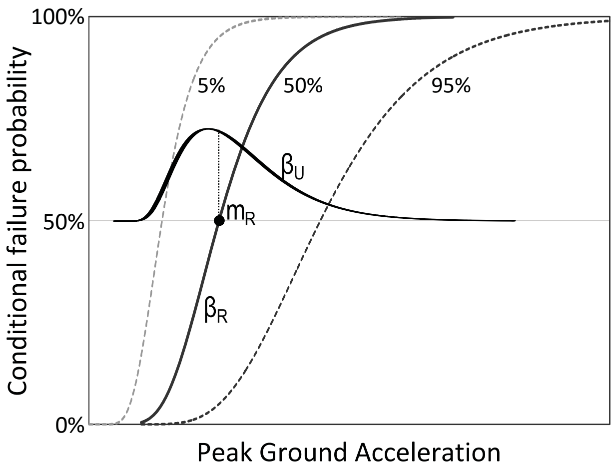

Figure 3: Example of family of seismic fragility curves for a structure. Adapted from [26].

curves defining the fragility, all have the same β_R and this family characterizes both uncertainties, as shown in Figure 3.

A family of fragility curves provides more information about uncertainty than a single fragility curve that considers natural and epistemic uncertainty combined. Figure Figure 4 idealizes graphically the difference in the resulting fragility curves of these two approaches.

3. The sliding failure mode in gravity dams

The sliding failure mode in concrete gravity dams addresses the 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 [29]. In fact, analysis of this failure mode is usually a key point of concrete dams' safety reviews. The safety evaluation is typically done using the factor of safety concept, which in general is defined as the ratio between the resistant forces and the driving forces along a giving sliding surface.

In the professional literature, a wide range of deterministic numerical and mathematical models can be found to analyze sliding safety of concrete dams, from 2D limit equilibrium models, which are the most common in international guidelines and regulations, to complex 3D finite element models [30, 31, 32, 33].

In the context of risk and reliability analysis, the most common approach to analyze sliding failure mode is using fragility curves, which combine condi-

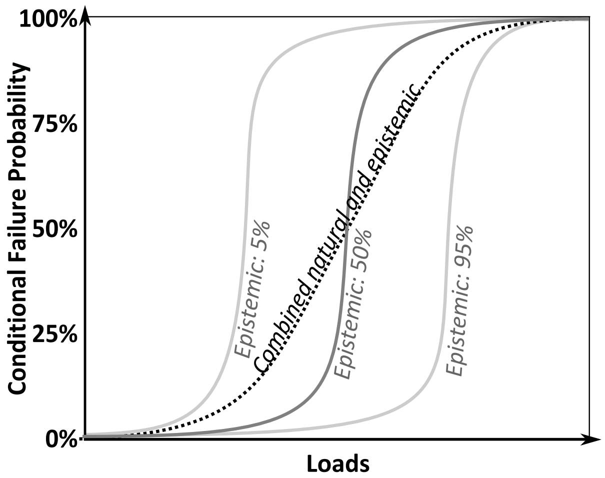

Figure 4: Differences when natural and epistemic uncertainties are separated versus when combined into one only fragility curve.

tional failure probability of the dam for different scenario conditions. These curves represent the system response in the risk model, as explained in the previous section. In general, for a defined loading state, a dam could fail due to different failure modes, controlled by different failure mechanisms. Commonly, fragility curves are defined for each failure mechanism separately and the individual mode fragilities are combined using classical system reliability techniques [4]. Therefore, sliding probability is usually introduced in quantitative risk models through fragility curves, where it is combined with other failure modes to compute overall dam failure probability and risk.

Other approaches followed to address uncertainty in the sliding failure mode has focused on the uncertainty of the hydrological loads and their relation with the system response [34] or on the spatial variation of foundation properties using geostatistical techniques [17].

In the context of risk and reliability analysis, the most common approach to analyze sliding failure mode is analyzed through a conditional failure probability of the dam for different scenario conditions, representing the system response in the risk model, as explained in the previous section.

In the literature, some examples can be found on the calculation of fragility curves for sliding of concrete dams and their use in risk models to compute failure probability [25, 20, 35, 13, 19]. In these examples, fragility curves are computed combining deterministic numerical models with reliability techniques. In each numerical model, different random variables are defined and then sampled to compute failure probabilities by analyzing the dam stability for different loading cases. In general, random variables distributions are based on local measurements and in-situ tests of foundation characteristics and drainage system behavior. The random variables defined and the numerical models used are different in each example.

However, these examples all present a significant disadvantage, since natural and epistemic uncertainties are addressed together when obtaining the fragility curves [13]. In fact, in general, a lot of effort has been put into very advanced reliability methods and numerical models, but less effort has been put into the input parameters estimation [20]. Thus, uncertainty in input data can have an overwhelming influence on the resulting failure probability [36].

In this context, addressing epistemic and natural uncertainty separately as proposed in this paper will help identify: 1)the main gaps of knowledge and 2)the effect on the computed failure probability of actions to reduce the epistemic uncertainty (new in-situ/laboratory tests, better monitoring system, analysis with numerical models, etc.).

4. Procedure for sliding failure fragility analysis

In this section, a procedure is presented to estimate a family of fragility curves that addresses natural and epistemic uncertainty independently for risk-informed dam safety management. This procedure combines the conceptual framework used in the nuclear industry explained in Section 2 with the existing methods for fragility curves estimation in concrete dams explained in Section 3.

The proposed procedure includes the following steps:

Step 1 Define the mathematical or numerical model that simulates the physical problem. As explained in the previous section, different models can be used to analyze sliding failure, form simple limit equilibrium models to complex non-elastic models [25]. The selection will depend on the complexity of the problem analyzed and the quantity and quality of data available. The performance of the model selected is also a source of epistemic uncertainty that should be analyzed in Step 8.

Step 2 Define the loading range and the number of loading cases analyzed to estimate the fragility curve. For the sliding failure mode, loadings are usually represented by the reservoir elevation, since water pressure and uplift are the driving forces for this failure.

Step 3 The working team has to assess which variables of the model will be considered as subjected to none or very low uncertainty, and which variables have necessarily to be treated as random. Typically, for the sliding failure mode, most of the uncertainty lies on the foundation strength and the magnitude of pore water pressures in the foundation soils, including the soil along rock discontinuities, or uplift pressures along such rock discontinuities.

Step 4 Two different distributions should be defined for each random variable: one for natural uncertainty and one for epistemic uncertainty. Mean values, standard deviations and probability distribution should be estimated, based on available data. In order to follow the conceptual framework explained in Section 2, it is proposed that both distributions should have the same mean, while the standard deviations and the probability distribution will depend on the natural and epistemic uncertainty. As explained in Step 7, the distribution defined for the epistemic uncertainty is a distribution of means of the random variables. The use of the mean to define random distributions is recommended, since it represents the expected value of the parameters and and its estimate is relatively stable for small sample sizes, in contrast to the median. Typically used probability distribution, include uniform, normal, log-normal, triangular, and beta distributions.

Distinguishing and defining probabilistic distributions for both types of uncertainty based on tests and measurements data can be difficult and quite subjective. The focus of this paper is not this distinction, which has been widely discussed by several authors [37, 11, 38]. In any case, when these distributions are defined, the working team should keep in mind that the random uncertainty represents the natural variation while the epistemic uncertainty is the part of the uncertainty that cannot be reduced with more test and computations, including the consideration of uncertainty due to not knowing what we do not know.

Step 5 Select the reliability method that will be used in the model to estimate failure probability. Some examples of these methods are First Order Second Moment (FOSM), Taylor's Method, Point Estimate Method

(PEM), Advanced Second Moment (ASM) Hasofer-Lind Method and Monte Carlo Method [25, 39, 40, 41]. Different reliability methods can be chosen for epistemic and natural uncertainty.

Step 6 For each loading case, compute the conditional failure probability using the selected reliability method for the natural uncertainty. In this step, values of the random variables are selected based on the chosen reliability method (Step 5) and the probability distributions defined for the natural uncertainty (Step 4). Therefore, different computations of the numerical model (Step 1) are made with these selected values to estimate failure probability.

When failure probability is represented versus loading range, the fragility curve capturing natural uncertainty is obtained. This curve is called "reference fragility curve" since it is computed only with the probability distribution for the natural uncertainty, without considering epistemic uncertainty. The "reference fragility curve" is equivalent to the fragility curve that could be obtained following the other existing methods to obtain fragility curves explained in the previous section (if they would only consider the natural uncertainty). Using only this reference fragility curve based on aleatoric uncertainty could underestimate the actual failure probability due to effect of the epistemic uncertainty. This additional uncertainty can be captured in the adjustment proposed in Step 7.

Step 7 First, groups of random variables are selected in the epistemic uncertainty distributions following the reliability method chosen for the epistemic uncertainty.

Second, for each selected group of random variables, a new probability distribution is defined for the natural uncertainty, using as "new mean" these selected values and keeping the same standard deviations and probability distributions defined for the natural uncertainty. Afterwards, for each group of random variables, Step 6 is followed to estimate the corresponding fragility curve using the new probability distribution defined for natural uncertainty. Therefore, the differences between the fragility curves are the mean values of the probability distributions of the random variables used to compute them. As a result, the family of fragility curves obtained separately captures both the epistemic and natural uncertainty. In order to obtain the structure of curves and parameters shown in Figure 3, median (logarithmic mean) can be obtained based on these results.

Step 8 Check the outcomes and perform sensitivity analysis on any of the decisions previously taken. This last step is a crucial, as the engineer should never get lost in any mathematical approach that may not represent sound engineering judgment.

The same structure followed in this method can be applied to other failure modes and dams' typologies to obtain fragility curves. Particularly for those failure modes of essentially "structural" nature, this method can be carried out rather straightforwardly due to its generic formulation.

Finally, this family of fragility curves can be introduced into a complete and quantitative risk model to estimate failure probability and risk, analyzing the effect of reducing epistemic uncertainty in the risk results.

5. Case study: Spanish concrete dam

The procedure described in the previous section is applied here to estimate a family of fragility curves for the sliding failure mode in a Spanish concrete dam. In this case, sliding along the concrete-foundation interface was considered for the central section. This section presents a triangular profile, as shown in Figure 5, with slopes of 0.05/0.76 (Upstream/Downstream). The dam crest level is at +911.4 meters and the foundation level is at +915.2 meters The height of the cross section is 96.2 m above the foundation. The maximum operating level in the reservoir is +908.5 meters. The dam is located over a sub-vertical layer of quartzite of 70 m depth. These quartzites have cracked and split into fragments due to the effect of its fold. Vertical cracks are predominant due to the strong vertical folding.

According to previous analyses and studies, the engineers in charge of this dam had doubts about the safety of this dam for the sliding failure mode. For this reason, risk analysis was applied to estimate the current risk for the sliding failure mode in the dam and to propose potential risk reduction measures and/or measures to reduce epistemic uncertainty. Epistemic uncertainty was significant in this case, due to the lack of data about the original design and the foundation characteristics, so it was considered that separating both types of uncertainty was important for a proper risk-informed dam safety management.

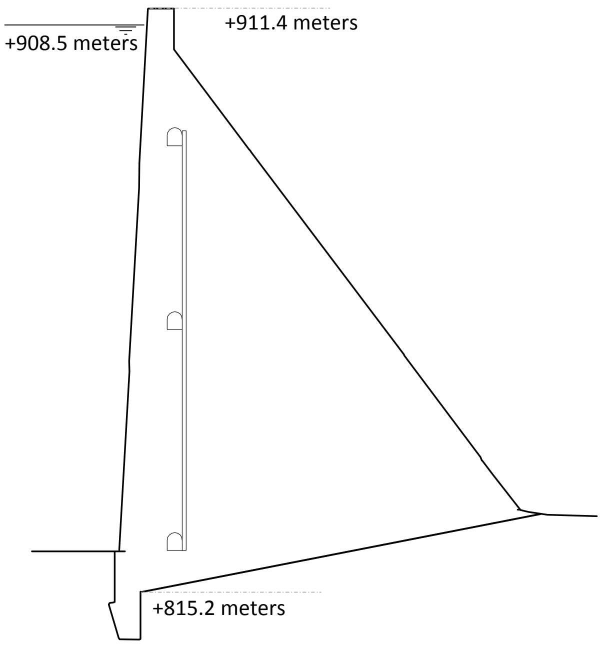

Figure 5: Cross section of the case study concrete dam.

Next, the steps presented in the previous section are followed to estimate the family of fragility curves and the risk profile in the dam, making a significant number of decisions that are justified as suitable for this particular problem.

Step 1. Identify the mathematical o numerical problem that represents the sliding failure mode. In this case, a 2D Limit Equilibrium Model was used to evaluate sliding failure along the foundation-concrete interface. The model includes a single interface in the contact between the dam and the foundation. This interface can mobilize tensile strength up to some limit value. The model allows for crack opening and propagation, with full uplift under the cracked zone of the dam base.

The limit-state function is defined as the ratio between the resistant force and the driving forces. In the cases where the driving forces are higher that the resistant forces, is considered that the dam would fail. The resistant force is supposed to be controlled exclusively by the friction angle and cohesion at the dam-foundation contact, following the classical Mohr-Coloumb equation:

$$R = (N - U) \cdot tan(\varphi) + B \cdot c \tag{2}$$

Where N are the normal forces acting on the contact (kN/m), U the uplift force (kN/m), φ is the friction angle $(^o)$, B is the compressed length on the contact (m), and c is the cohesion (kN/m^2).

The driving forces are the reservoir water pressure, the submerged sediments pressure and the uplift pressure. Water and uplift pressures directly depend on the water level in the reservoir.

Step 2. Define the plausible loading range that can produce the sliding failure. The selected variable to define the loading state in the dam is the maximum water level reached in the reservoir during any given hydrologic event, since water pressure is the main driving force of the sliding failure mode.

The selected range of pool levels comprises from +908 meters (0.5 meters under the maximum operating level) to +915.4 meters (4 meters above the dam crest level, for this level the overtopping failure mode would be clearly predominant). In total, 38 reservoir elevations (equally distributed every 0.2 meters within the range) were considered for calculations.

Step 3. Define which variables of the mathematical model will be treated as random. In this case, since the uncertainty on the foundation resistance capacity is the main concern, two independent random variables of the Limit

Equilibrium Model are considered based on an initial sensitivity analysis: friction angle (φ) and cohesion (c).

All the other variables are assumed to be known exactly, including geometrical parameters such as dam height, upstream slope, downstream slope, etc., material characteristics, such as concrete density, and performance parameters such as drain effectiveness (which considered as completely ineffective).

Step 4. Estimate two statistical distributions (for natural and epistemic uncertainty) for each of the random variables. Two probabilistic distributions have been estimated for both random variables as shown in Table 1. The estimation of these probabilistic distributions by expert judgement is a complex process which is out of the scope of this paper and it should be based on geotechnical in-situ and laboratory tests, measurements procedures and temporal and spatial variations of results. As can be observed, the same means are used for both types of uncertainty as stated in the previous section. The working team has evaluated which part of the uncertainty is due to natural variations in the foundation and which part could be reduced with more tests and data. The standard deviation has been considered higher for the epistemic uncertainty than for the natural uncertainty, due to the existing doubts about the dam foundation. The truncated normal distribution is used for the friction angle and the truncated lognormal distribution is used for the cohesion, as these are the distributions that best fit available data. This result is similar to others found in literature [42, 33, 43].

Random variable	Mean	St. Deviation	Maximum	Minimum	Type
		Natural uncertainty			
Friction angle	50^o	5^o	65^o	35^o	Normal
Cohesion	0.5 MPa	0.2 MPa	1.5 MPa	0.1 MPa	Log-Normal
		Epistemic uncertainty			
Mean friction angle	50^o	2.5^o	60^o	40^o	Normal
Mean cohesion	0.5 MPa	0.125 MPa	1 MPa	0.2 MPa	Log-Normal

Table 1: Estimated probability distributions for the random variables.

Step 5. Select the reliability method to estimate failure probability. The reliability method selected for both natural and epistemic uncertainty is the Monte Carlo with the Latin Hypercube Sampling (LHS) method. This method is chosen because the state function and calculation model selected in Step 1 are simple enough to allow many limit equilibrium computations to be rapidly made. Furthermore, for both types of uncertainty, 10,000 samples of random variables are made to define the family of fragility curves.

Step 6. Build the reference fragility curve. First, 10,000 pairs of values of the random variables (φ, c) have been sampled with the Latin Hypercube method in the probabilistic distributions for the natural uncertainty.

Second, for each water level, the Limit Equilibrium Model is used to define the limit curve for these two random variables [25]. The limit curve represents the values of the random variables (φ, c) that produced a resistance force equal to the driving forces. Conditional failure probability is estimated with the number of sampled values of the random variables that are located under the limit curve (failure cases). For example, this process is represented in Figure 6 for one water level (among the 38 water levels considered).

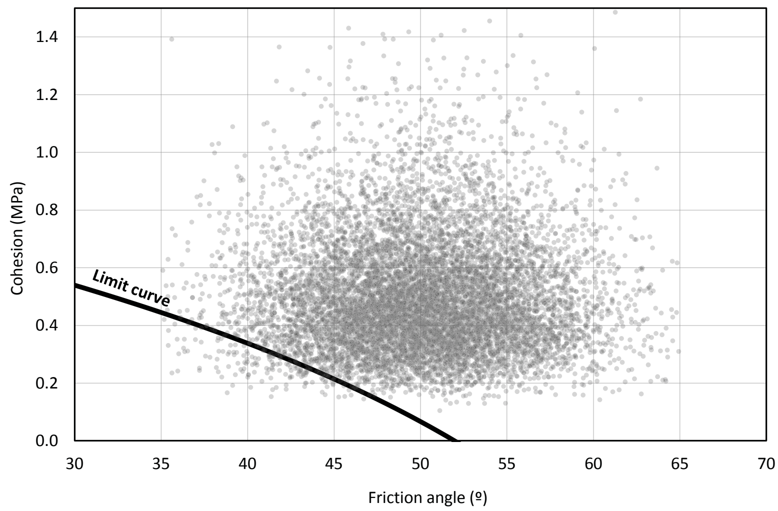

Figure 6: Limit curve for pool water level 911.4 meters (Conditional failure probability = 1.75%).

When conditional failure probability is represented versus pool water level, the reference fragility curve is obtained. This curve only reflects aleatory uncertainty and it is shown in Figure 7. The obtained curve shows that, according to the chosen mathematical model, the dam has a quite fragile response for the sliding failure mode, since the curve changes from 0% to 100% conditional failure probability with a difference of 4 meters in the pool water level.

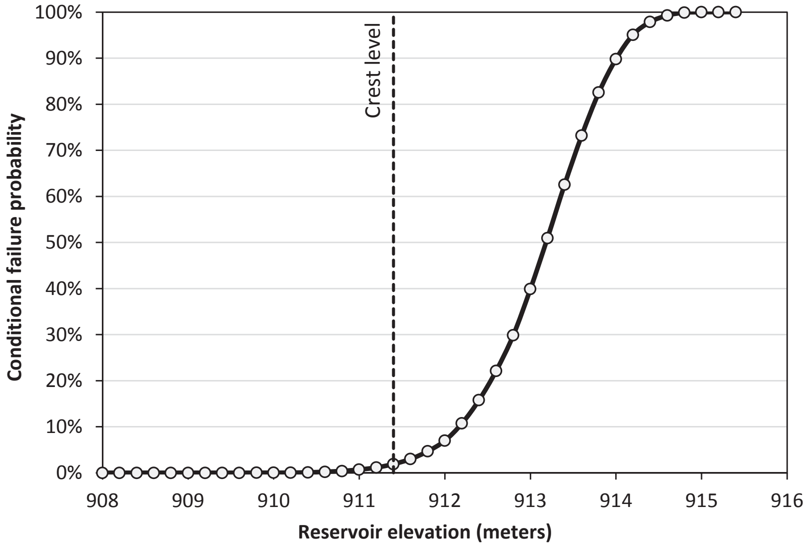

Figure 7: Reference fragility curve for the case study.

Step 7. Build the family of fragility curves combining the probability distributions defined for epistemic and natural uncertainties. In this step, a family of 10,000 fragility curves is obtained to characterize epistemic uncertainty. First, 10,000 couples of values of the random variables (φ, c) have been sampled with the LHS method in the probabilistic distributions for the epistemic uncertainty.

Second, each couple of values has been used to define two new probabilistic distributions for φ and c. In these distributions, the sampled values are the mean, while the type of distribution and the standard deviation are the same that in the natural uncertainty probabilistic distribution.

Third, for each couple of values, Step 6 is applied to obtain a fragility curve using the new probabilistic distributions for φ and c. Therefore, 10,000 fragility curves are obtained, one for each pair of values. In order to obtain all these fragility curves, the dam stability is checked 38 (number of water levels) x 10,000 (number of curves) x 10,000 (number of sampled values to estimate failure probability) = 3.8 billion times. The family of fragility curves obtained is shown in Figure 8.

Figure 8 provides very useful information for dam safety governance and decision making. For instance, it indicates that at the current crest elevation

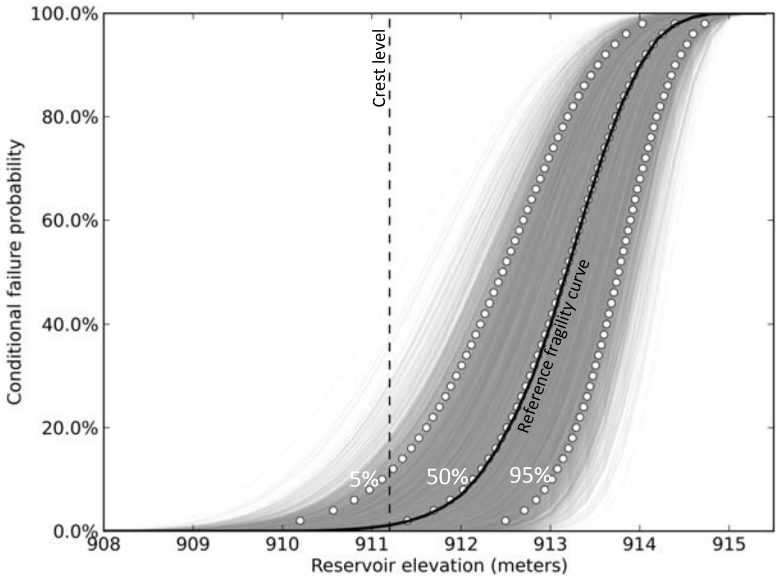

Figure 8: Family of fragility curves obtained for the case study.

of 911.5 meters, there is a level of confidence higher than 95% that the dam will not fail by sliding, since probability of failure for the 5% curve is lower than 20%. In addition, probability of sliding failure is very low for reservoir elevation lower than 909 meters.

As can be observed in this figure, these fragility curves are not parallel, since there are two independent random variables. The spread of this family is an indicator of the influence of the epistemic uncertainty in the results. Furthermore, in order to follow the EPRI framework (Section 2), the standard deviation β_U can be obtained representing the histogram of the median of the curves (conditional probability = 50%), as shown in Figure 9. In this case, the standard deviation of this probability distribution is 0.40 meters and the median +913.17 meters.

Step 8. Check results and re-evaluate previous decisions. In this step, the different decisions made in the previous steps should be reviewed and the obtained results should be checked. The simple Limit Equilibrium Model selected for this analysis has allowed completing a high number of stability computations in order to explain the proposed procedure in detail. Although, this simple model is also a source of epistemic uncertainty that could be

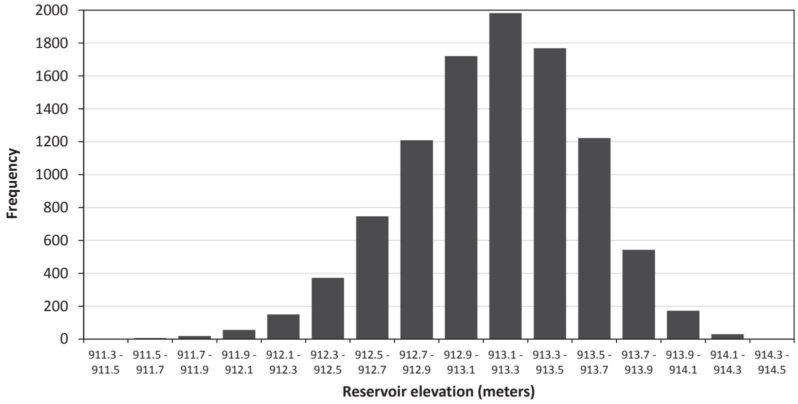

Figure 9: Histogram of the median in the 10,000 fragility curves.

evaluated comparing it with more complex stability models.

One of the issues that has a higher influence in the results and the calculating times is the number of samples of the random variables chosen to estimate failure probability. In order to analyze the effect of this decision, the failure probability within the reference fragility curve has been re-estimated depending on the number of samples for three different maximum water levels: +912, +913 and +914 meters Results are shown in Figure 10.

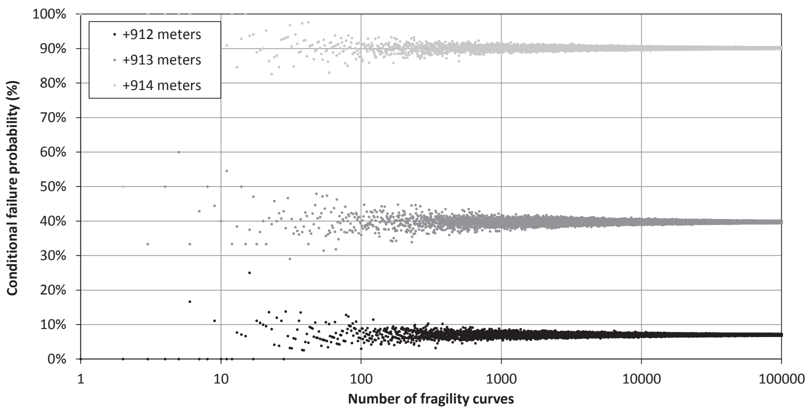

Figure 10: Failure probability for three reservoir elevations as a function of the number of samples used to compute them.

As can be perceived in Figure 10, failure probability results are stable when the number of samples is higher than 1,000, so 10,000 samples is a good decision to achieve accurate results.

Next, the number of fragility curves needed to properly characterize epistemic uncertainty is addressed. In this case, the standard deviation of the histogram of the fragility curves family has been estimated as a function of the number of fragility curves used to compute it for three different conditional failure probabilities (5%, 50% and 95%). This standard deviation is an indicator of the spread of the family of fragility curves.

As can be observed in Figure 11, standard deviation results are stable when the number of fragility curves is higher than 1,000. Therefore, 10,000 fragility curves seems a good decision.

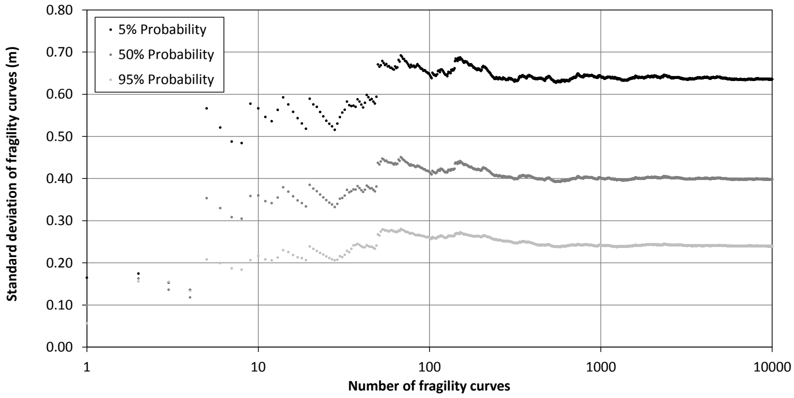

Figure 11: Standard deviation of the histogram of the fragility curves family as a function of the number of fragility curves considered.

6. Discussion and final remarks

The paper formulates a comprehensive procedure for fragility analysis of sliding failure of concrete gravity dams making use of reliability methods and formally distinguishing two main sources of uncertainty, natural and epistemic. The suggested eight step framework focuses on the options and decisions that an analyst has to face, trying not to hide crude real world decisions behind the elegance and accuracy of mathematics. As a matter of fact, fundamental issues remain to some extent unsolved and it is not our intention to avoid the debate, on the contrary, we believe that any innovation or advance in analysis techniques should facilitate it. Some conceptual and operational precautions have been observed. Namely:

- Friction and cohesion (in the case study presented in this paper) but also other variables potentially representing "relevant data" to other cases, such as uplift or ice load pressure, are quite difficult to fully characterize by means of empirical data, regardless the number of data available, due to facts such as imperfect testing and/or non fully reliable measuring techniques among other reasons. Indeed, the independence hypothesis among them is not universally agreed, or strongly contested.

- The impact on the results of the choice of the probability distributions has been addressed. Defining separated probability distributions for natural and epistemic uncertainty is a complex process that should be based on tests data and expected model and measurements errors.

- This framework is focused on the system response term of the risk equation, but distinguishing natural and epistemic uncertainty is also necessary when loads and consequences are addressed. Therefore, uncertainties can be propagated in the risk equation through convolution.

- Nevertheless, the more the procedure decomposes the process, and the more decisions and options are subjected to open discussion and scrutiny, as we think our procedure does, we truly believe that results are more meaningful for understanding the risks and informing decision making.

On the other hand, the separation of epistemic uncertainty and natural variability following the proposed methodology is not only an academic exercise, but strong practical implications can be followed from this separation in the everyday safety management decisions. It is worth considering that:

- The impact of the epistemic uncertainty span on the overall risk picture appears as valuable information regarding the design and urgency of the actions needed to reduce the gap in knowledge and so to improve the safety of the dam.

- The decision-maker is provided with information of the estimated residual risk level expected after gaps in knowledge have been filled. By deriving a probability function estimate for natural variability, the working team is expressing a minimum value regarding how much uncertainty is going to be assumed by the owner on the current situation, given that the gaps in knowledge are filled, without further risk reduction measures.

- This residual risk picture generated by natural variability can be used to inform the design of additional risk reduction measures aimed to reduce the loading probability or to reduce the failure probability.
- In addition, having adopted the EPRI distinction between epistemic and natural variability, brings together the practices of two different industries, nuclear and dams, favoring a needed dialogue for performing analysis such as the nuclear risk assessment for facilities that can potentially be flooded by failure of upstream dams.

Finally, it is worth to mention that the intent of the authors is coping with uncertainty, more than fighting against uncertainty, which is identified as one of the main elements of "smart governance" [44].

7. Acknowledgements

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Annex 5

Dealing with epistemic uncertainty in risk-informed decision making for dam safety management

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Dealing with epistemic uncertainty in risk-informed decision making for dam safety management

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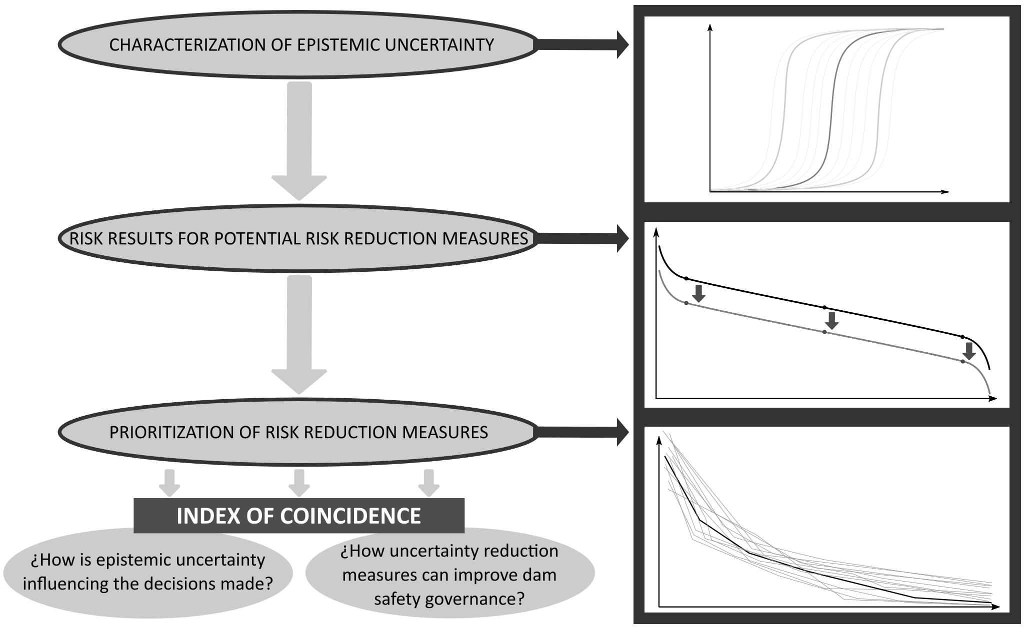
ABSTRACT

In recent years, the application of risk analysis to inform dam safety governance has risen significantly. In this framework, considering explicitly and independently natural and epistemic uncertainty in quantitative risk models allows to understand the sources of uncertainty in risk results and to estimate the effect of actions, tests and surveys to reduce epistemic uncertainty. These two types of uncertainty can be differentiated in the three parts of the risk equation: loads, system response and consequences.

In this paper, Indexes of Coincidence are proposed to analyze the effect of epistemic uncertainty in the prioritization of investments based on risk results. These indexes allow considering the convenience of conducting additional uncertainty reduction actions, like site tests, surveys or more detailed analysis.

Finally, these metrics have been applied to the prioritization of risk reduction measures for four concrete gravity dams in Spain. Results allow a better understanding of how epistemic uncertainty of geotechnical resistant parameters influences risk-informed decision making. Results also help to define the need for additional tests and surveillance actions.

GRAPHICAL ABSTRACT



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1. INTRODUCTION

There is nowadays a trend towards seeing dam safety as an active and ongoing management process rather than a static and deterministic statement. Tools such as risk analysis can be useful to help owners take risk-informed decisions. Risk assessment helps engineers to understand uncertainties in critical infrastructures, and provides a logical process of identifying hazards, evaluating system response and vulnerabilities associated to each hazard, and assessing the effectiveness of risk reduction measures.

In recent years, risk assessment techniques have been developed worldwide and applied in the dam industry to inform safety governance (1–4). These guidelines and recommendations have been developed within the tolerability of risk (TOR) framework, which was set out by UK's HSE (5) for risk evaluation and management. The current paper is contextualized within this framework.

However, the contextual information provided above is wide more complex than it may sound, veiling many theoretical and practical difficulties. Many of these difficulties are related to how uncertainties are explicitly considered today (in the context of risk analysis), in opposition to the more traditional implicit treatment (in the context of state-of-the-art dam safety practice).

When risks of complex structures are analyzed, evaluation of uncertainty should play an important role in the analysis of the behavior of a constructed facility (6). In general, two sources of uncertainty are considered (7–9):

- **Natural uncertainty or randomness:** Produced by the inherent variability in natural processes. An example is the variability of the loads that the structure has to withstand, for instance, the variability in the potential floods magnitude that can occur. This type cannot be reduced, though it can be estimated.
- **Epistemic uncertainty:** Resulting from not having enough knowledge or information about the analyzed system. This lack of information can be produced by deficiency of data or because the structure's behavior is not correctly represented. The more knowledge is available about a structure or system, the more this type of uncertainty can be reduced.

In the dam safety field, both types of uncertainty are generally introduced together in risk model inputs, without specifically distinguishing the effect of epistemic uncertainty. These results are very useful to prioritize risk reduction investments, but still two important questions for dam safety governance remain unanswered:

- How is epistemic uncertainty influencing the decisions made based on risk results?
- How can potential uncertainty reduction measures (geotechnical tests, dam computational models, improvements in dam surveillance and monitoring…) improve dam safety governance?

In order to solve these questions, this paper presents two indicators named Indexes of Coincidence that measure the effect of epistemic uncertainties in risk-informed decision making. These indexes are computed comparing the effect of epistemic uncertainty in prioritization sequences of potential risk reduction measures. These sequences of measures are obtained with the procedure developed in (10).

These Indexes of Coincidence have been obtained to inform safety management in four existing concrete gravity dams in Spain. These real examples illustrate how the proposed

Indexes of Coincidence can provide useful information to answer the two previous questions.

2. UNCERTAINTY IN RISK MODELS FOR DAMS

Risk is the combination of three concepts: what can happen, how likely is it to happen, and what are its consequences (11). Following this definition, in the dam safety field, risk is usually quantified with the following equation (12):

$$Risk = \int P(loads) \cdot P(response|loads) \cdot C(loads, response) \qquad \text{Eq. 1}$$

where the integral is defined over all the events under study, *P(loads)* is the probability of the different load events, *P(response|loads)* is the conditional probability of the structural response for each load event and *C(loads,response)* are the consequences of the system response for each load event. In the dam safety field, the system response analyzed is the dam failure. Consequences can be introduced in economic terms to obtain economic risk or in terms of potential loss of life, to obtain societal risk (10).

These terms of the equation are usually analyzed independently and they can be combined within a quantitative risk model to compute dam failure risk. Risk models are commonly created through event trees (3,13), which analyze the different ways in which a dam can fail (failure modes) calculating their associated probabilities and consequences. An event tree is a representation of a logical model that includes all the possible chains of events resulting from an initiating event that can produce the structural failure (SPANCOLD, 2012). Defining each of the probabilities along these chains of events, the overall failure probability and risk of the structure can be obtained. Figure 1 shows an example of the graphical representation of this type of trees.

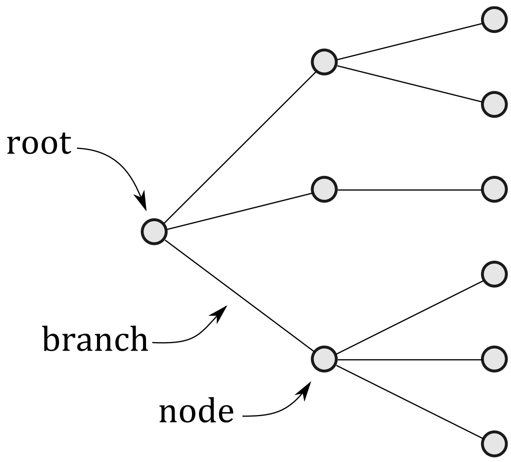

Figure 1: Example of event tree. Source:(3).

Each node of the tree represents an event. The root node is called initiating event. Branches that grow from an event represent the possible outcomes of their event of origin. Branches must represent mutually exclusive and collectively exhaustive events so an event will always be reflected in a single fashion in only one branch. In this way, if a probability is assigned to each possible outcome (for every event), the addition of all probabilities of the outcomes arising from any node should be 1. Probabilities in event trees, except for the initiating event, are always conditional, that is, for any intermediate node it is assumed that all preceding events (parent nodes) have already happened.

In these risk models for dams, natural and epistemic uncertainties are not usually introduced separately. They are usually mixed in the probability input data introduced for the structural response with a mean conditional failure probability for each loading state (14). This approach is called first-order probabilistic risk analysis (15) and it is the most common approach in risk-informed dam safety management (2,3,13).

As a result of applying Equation 1 in the event tree, a single value of failure probability and risk is obtained. If consequences are expressed in terms of loss of life, FN curves can be derived to represent the relation between loss of life and exceedance probability. The area under these curves is equivalent to the societal risk (16).

First-order probabilistic risk analysis represents Level 4 of complexity in the classification developed by (17). There is a higher level of complexity to fully represent both types of uncertainty (Level 5), called second-order probabilistic risk analysis. In this level, epistemic and aleatory uncertainties are introduced separately in the risk model, defining probability distributions for input data in the risk equation.

In order to carry out calculations in Level 5 models, the two types of uncertainty can be addressed using a two-loop Montecarlo analysis (18). In the upper loop, random variables with epistemic uncertainty are sampled. These sampled values are used to compute risk in the lower loop. Another option can be to combine epistemic uncertainty variables sampling in the upper loop of Montecarlo analysis with event trees. Hence, a risk result is obtained for each group of sampled values with the event tree (19,20). In both approaches, when risk results are ordered, a risk probability distribution is obtained.

Hence, in a second-order probabilistic risk analysis, a risk probability distribution and a family of FN curves are obtained instead of a single value and curve, as explained in (15,20). The spread of risk probability distribution and the family of FN curves thus represents the degree of epistemic uncertainty in the risk assessment. In Figure 2, the type of risk results and risk representation are compared for first-order and second-order probabilistic risk analyses. Second-order probabilistic risk analysis is more common in other industries like the nuclear industry (21).

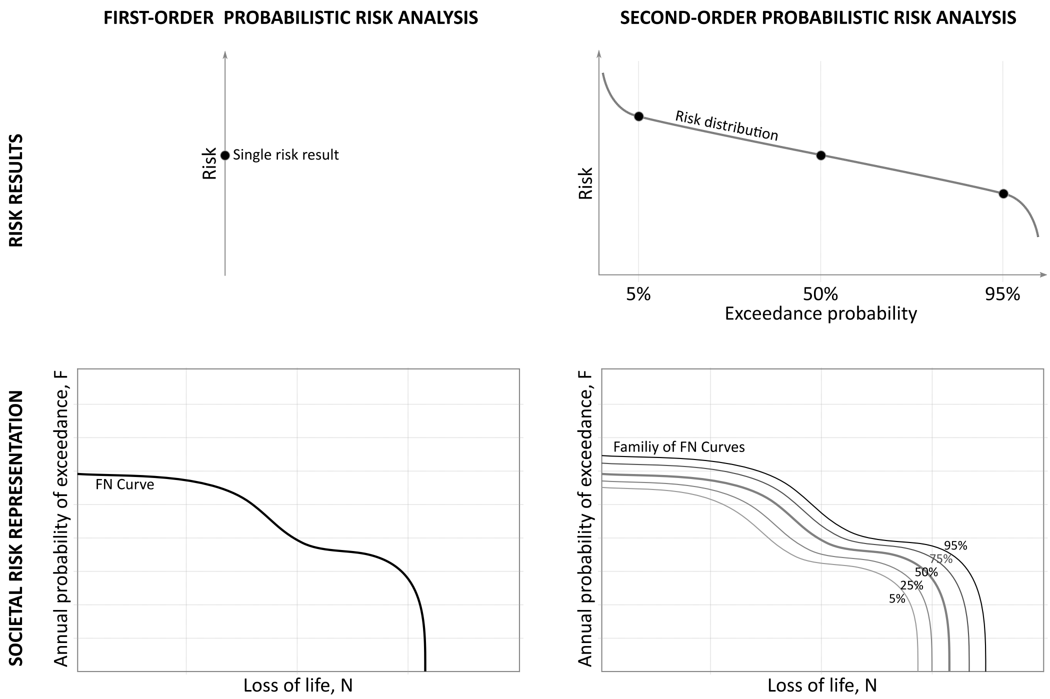

Figure 2: Comparison of risk results and risk representation between first-order and second-order probabilistic risk analysis.

In recent years, different research studies have been developed to characterize epistemic uncertainty in input data of quantitative risk analysis. As explained above, the separation of epistemic and aleatory uncertainties in input data is the first step for a second-order risk analysis. Following the three terms of the risk equation (Equation 1), the existing approaches that can be followed to make this separation are:

- **Probability of loading:** This part of the equation typically makes reference to the probability of severe flood events and their subsequent reservoir elevations (hydrological scenario) or severe seismic events (seismic scenario).

  In hydrological scenarios, in general a probability distribution for reservoir elevations is introduced in the risk model obtained from the probability of flood events, probability of previous pool levels in the reservoir and probability of availability of outlet works (22,23).

  In order to separate both types of uncertainty, main epistemic uncertainties in the rainfall-runoff and flood routing process should be characterized. Different families of inflow hydrographs in the reservoir can be obtained based on a parametric rainfall-runoff analysis (24) and they can be combine with previous pool levels and gates availability to obtain a family of probability distributions for reservoir elevations (or volumes) in the reservoir (25). The spread of this family of curves represents the degree of epistemic uncertainty in the hydrological loading.

  In seismic scenarios, epistemic and aleatory uncertainties of seismic loading could be separated as it is made in the nuclear industry (21). Hence, different families of seismic events could be generated to compute failure probability instead of a single Annual Exceedance Probability-Ground acceleration curve (20).

- **Probability of system response:** This part of the equation is addressed through fragility curves, which represent a relationship between conditional failure probability and the magnitude of loads that produce failure. In (14), a procedure is introduced to perform fragility analysis for dams in order to identify and track natural and epistemic uncertainty separately. This procedure is particularized for the sliding failure mode of concrete gravity dams and it is based on the concepts by (26) to develop seismic fragility curves for the nuclear industry. As a result of this procedure, a family of fragility curves is obtained to characterize the sliding failure, as shown in Figure 3. The spread of this family is an indicator of the influence of the epistemic uncertainty in the results.

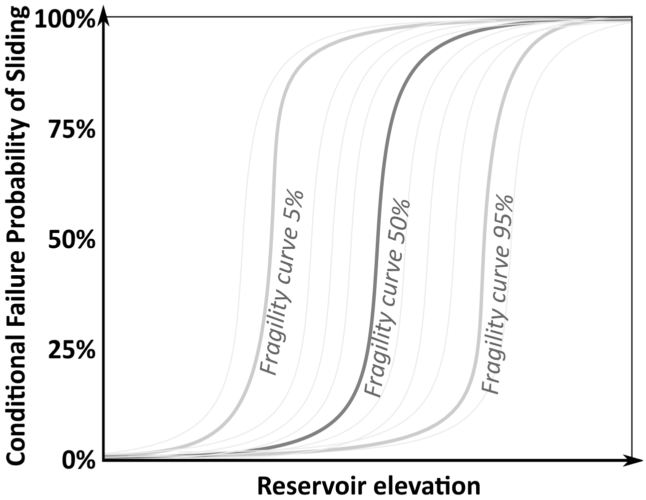

Figure 3: Example of family of fragility curves for sliding failure mode. Adapted from (14).

The same concepts have been followed to obtain a family of fragility curves for other failure modes in dams, like embankment instability (19) and overtopping (20).

- **Dam failure consequences:** In first-order probabilistic risk analysis, a single value of economic consequences or loss of life is used in each branch of the event tree to compute risk. In order to include epistemic uncertainty, a probability distribution of consequences could be introduced in each branch of the event tree. These probability distributions can be obtained based on epistemic uncertainties in hydraulic models (27) and warning and evacuation procedures (20,28).

3. RISK-INFORMED DECISION MAKING FOR DAM SAFETY MANAGEMENT

Once risk results are computed, they are used to inform dam safety management. In general, risk analysis to inform dam safety governance is contextualized within the Tolerability of Risk (TOR) framework developed by (5) for risk evaluation and management. This framework has been widely used worldwide to define risk-informed dam safety programs (2–4,29). According to this framework, two basic principles are generally used to guide decision making (1,5):

- **Equity:** This principle is based on the premise that all individuals have unconditional rights to certain levels of protection. This principle is applied through the individual risk, which can be defined as the probability that at least one person dies as a result of the dam's failure (3).
- **Efficiency or utility:** This principle arises from the fact that society possesses limited resources, which must be spent in the most efficient way. When considering several risk reduction measures, the one producing a higher risk reduction at a lower cost (the one that optimizes expenditure) should generally be chosen first.

When quantitative risk analysis is applied to inform safety management of portfolios of dams, a high number of results are obtained. In this context, risk reduction indicators have proved to be a useful tool to prioritize risk reduction measures (10,30,31). These indicators are numeric values obtained for each potential risk reduction measure considered based on its costs and the quantitative risk reduction it provides. Risk reduction indicators are directly related with equity and/or efficiency principles and they are computed based on risk results obtained for each considered measure with a first-order probabilistic risk analysis.

In (10), a procedure to obtain prioritization sequences based on risk reduction indicators is introduced. In each step of the sequence, the measure with the lowest value of the indicator is chosen. The obtained prioritization sequence depends on the risk reduction indicator used to define it. Prioritization sequences can be represented in variation curves (Figure 4), which represent the variation of the aggregated risk in the portfolio as measures are implemented. In the X axis, annualized costs or implementation steps can be displayed while in the Y axis aggregated individual risk, societal risk or economic risk can be shown. Depending on what is represented in each axis, the risk reduction indicator that will lead to the optimum sequence is different.

Existing risk reduction indicators to compare different investment alternatives are reviewed in (10), analyzing the relation between risk reduction measures and equity and efficiency principles. In dam safety management, two indicators are predominant in the evaluation of risk reduction measures:

- **CSLS (Cost per Statistical Life Saved):** (2,5) This indicator shows how much it costs to avoid each potential loss of life as a result of a dam failure. It is widely used to manage quantitative risk results in different fields (32–35). Its value is obtained through the following formula:

$$CSLS = \frac{C_a}{r_s(base) - r_s(mea)} \quad \text{Eq. 2}$$

Where $r_s(base)$ is the risk expressed in loss of lives for the base case, $r_s(mea)$ is the risk in lives after the implementation of the measure and C_a is the annualized cost of the measure including its annualized implementation costs, annual maintenance costs and potential changes in operation costs produced by the adoption of the measure. CSLS compares costs with societal risk reduction, so it is directly related with the principle of efficiency.

- **ACSLS (Adjusted Cost per Statistical Life Saved):** (2,36) This indicator has the same structure as CSLS but introduces an adjustment of the annualized cost to consider the economic risk reduction generated by the implementation of the measure. It is obtained with the following equation:

$$ACSLS = \frac{C_a - (r_e(base) - r_e(mea))}{r_s(base) - r_s(mea)} \qquad \text{Eq.3}$$

Where $r_e(base)$ is the economic risk of the infrastructure for the base case and r_e *(mea)* is the economic risk after the implementation of the measure. It is also based on the efficiency principle.

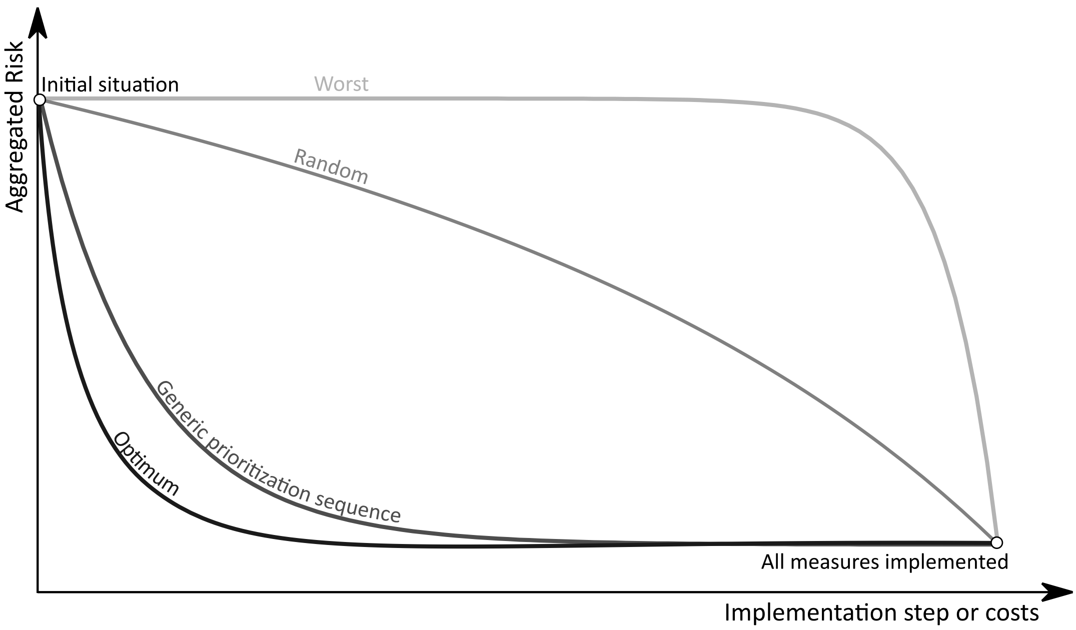

Figure 4: Generic representation of variation curves to define prioritization sequences. Source: (31).

Finally, in (31) a new risk reduction indicator is introduced to combine equity and efficiency principles: **Equity Weighted Adjusted Cost per Statistical Life Saved (EWACSLS)**. This indicator is computed with the following formula:

$$EWACSLS = \frac{ACSLS}{\left(\frac{\max(r_i(base), IRL)}{\max(r_i(mea), IRL)}\right)^n} \qquad \text{Eq. 4}$$

Where $r_i(base)$ is the individual risk for the base case expressed in years^{-1}, $r_i(mea)$ is the individual risk in years^{-1} after the implementation of the measure, *IRL* stands for Individual Risk Tolerability Limit and n is a parameter that allows assigning a higher weight to either efficiency or equity in the prioritization process. As can be observed in Equation 4, if the individual risk is lower than IRL, the only prevailing principle is efficiency (through ACSLS), since the denominator of the formula is then 1. Thus, the equity principle only modifies the value of the indicator in the cases where individual risk is above tolerability thresholds.

In conclusion, risk reduction indicators are a useful tool to prioritize a high number of investments in a portfolio of dams based on quantitative risk results. However, this approach does not consider the effect of epistemic uncertainty in risk results separately. For this reason, these prioritization sequences are focused on risk reduction measures but they do not address the potential epistemic uncertainty reduction measures (better hydrological studies, more geotechnical tests, improved analysis of dam behavior…), which are also a key part of dam safety management.

4. INDEXES OF COINCIDENCE TO ANALIZE EPISTEMIC UNCERTAINTY IN DAM SAFETY DECISION MAKING

In dam safety management, two types of investments can be analyzed: risk reduction measures (higher outlets capacity, freeboard requirements…) and uncertainty reduction measures (geotechnical tests, dam computational models…). These two types of measures have a different impact on a risk probability distribution obtained by a second-order probability risk assessment. Risk reduction measures move the probability distribution downwards, while measures to reduce epistemic uncertainty produce a less steep risk distribution, as shown in Figure 5.

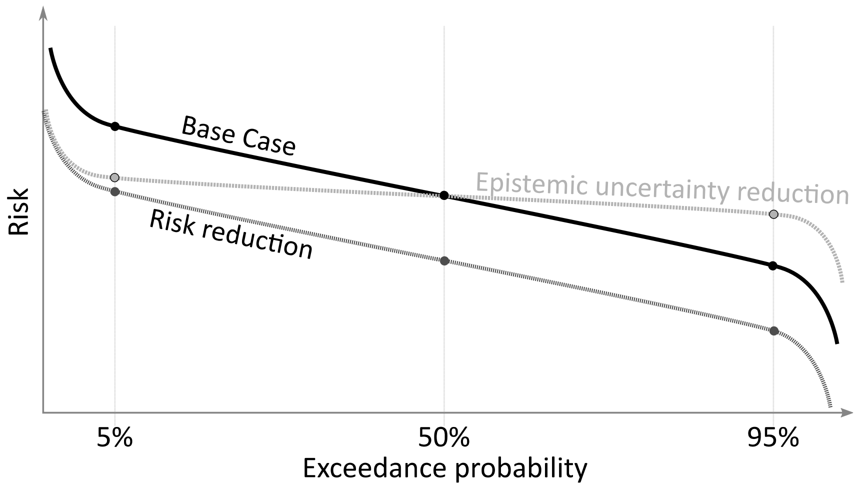

Figure 5: Example of the effect in a risk distribution of a risk reduction measure and an epistemic uncertainty reduction measure.

As explained in Section 3, current approaches to inform dam safety are focused on average risk results from first-order probabilistic risk analysis. For this reason, they are used to prioritize risk reduction measures but they do not analyze the effect of epistemic uncertainty. However, this type of uncertainty can influence decision making and prioritization sequences. For instance, in high epistemic uncertainty situations, the decisions made can change depending on the values considered within the epistemic uncertainty distributions.

As explained in Section 2, in a second-order probabilistic risk analysis a high number of risk results are obtained instead of a single risk value. The spread of these results indicates the existing epistemic uncertainty. Hence, a high number of risk results are obtained for the base case and for each risk reduction measure analyzed.

When these results are combined with the calculation of prioritization sequences explained in Section 3, a high number of sequences are obtained for each risk reduction indicator, instead of a single sequence for the average values. The differences between these high number of sequences indicate how epistemic uncertainty influences decision making. In a case where epistemic uncertainty is not influential, the order of the analyzed measures in all the sequences will be the same, while in a case with a high influence of epistemic uncertainty, there will be higher differences in the order of measures within the sequences. According to the authors, this is the key of dealing with epistemic uncertainty within dam safety management: analyzing how it can change the decisions made and when it is recommended to invest in reducing this type of uncertainty.

Based on this reasoning, two different indexes have been developed and proposed in this paper to measure the effect of epistemic uncertainty in the calculation of prioritization sequences. These metrics are based on the difference in the order of measures between each sequence obtained with the results of a second-order probabilistic risk analysis and the reference sequence obtained with the average values from first-order risk analysis. The two indexes developed are:

- **Index of Coincidence (IC):** It quantifies the difference in the order of measures between two sequences. It is computed with the following equation:

$$IC = \left(\sum_{i=1}^{N} 1 - {|pr_i - p_i|}\Big/{(\max(pr_i - 1, N - pr_i))}\right)/N \qquad \text{Eq. 5}$$

  Where N is the number of measures in the sequences compared, pr_i is the position of the measure i in the reference sequence and p_i is the position of the measure i in the sequence compared with the reference sequence.

  Figure 6 graphically shows how this indicator is computed in an example. For each step of the measure, it is computed with the division of the difference in the position of a sequence in the two itineraries (A in this figure) and the maximum difference in the position that there could be (B in this figure).

- **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. This adjustment factor varies from 2 for the first step of the measure to 0 for the last step. It can be computed with the following equation:

$$AIC = {\left(\sum_{i=1}^{N} IC_i \cdot \frac{2\cdot(N_i - p_i)}{N-1}\right)}\Big/{N} \qquad \text{Eq. 6}$$

  Where IC_i is the partial Index of Coincidence for measure i in the sequence, obtained with equation 5.

Table 1 illustrates how these two indexes are calculated for the example shown in Figure 6. In this table, AIC_i are the partial Adjusted Index of Coincidence for each step of the sequence, obtained with equation 6. The name of Index of Coincidence has been chosen based on the Index of Coincidence used in cryptography to analyze the similarity between two texts (37).

Thus, these indexes 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. Hence, a high number of Indexes of Coincidence are obtained, one for each sequence. The average Index of Coincidence of all these sequences 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.

With this approach, results of first-order probabilistic risk analysis can be used to define the reference prioritization sequence for risk reduction measures, while average Index of Coincidence indicate the influence of epistemic uncertainty and the need for uncertainty reduction measures.

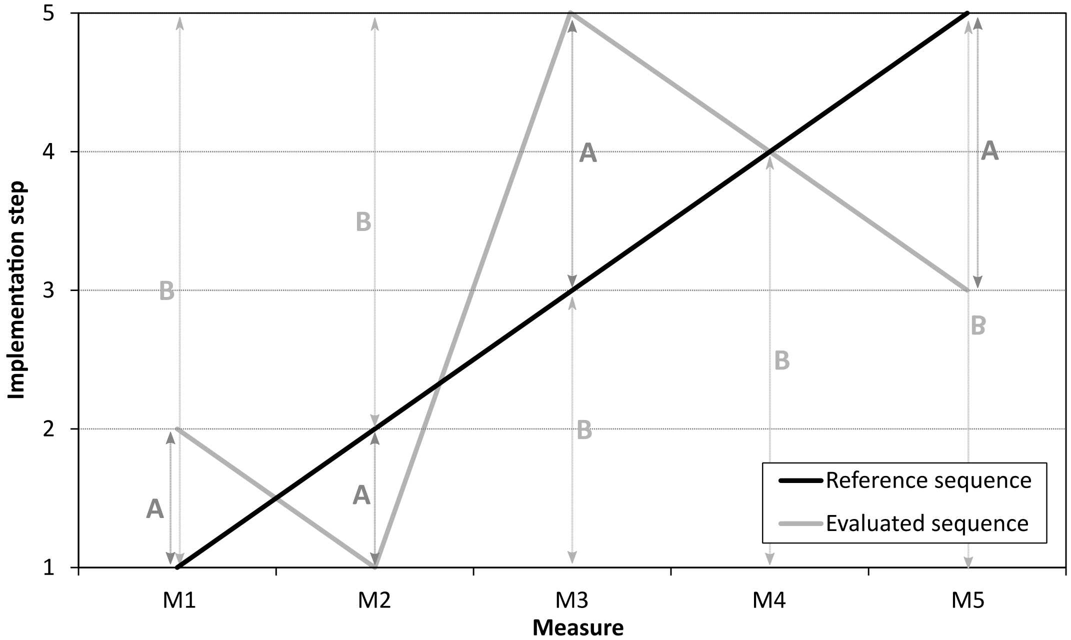

Figure 6: Graphical representation of Index of Coincidence to compare two prioritization sequences.

Measure	p_i	pr_i	Difference between itineraries (A)	Maximum possible difference (B)	IC_i	Adjustment factor	AIC_i
M1	2	1	1	4	75%	2	150%
M2	1	2	1	3	67%	1.5	100%
M3	3	3	2	2	0%	1	0%
M4	4	4	0	3	100%	0.5	50%
M5	5	5	2	4	50%	0	0%
Index of Coincidence					**58%**		
Adjusted Index of Coincidence							**60%**

Table 1: Example of calculation of Indexes of Coincidence to compare two prioritization sequences with five measures.

Although the average Index of Coincidence can be computed when epistemic uncertainty is introduced in the three parts of the risk equation, as explained in Section 3, they may be more useful when they are computed after introducing epistemic uncertainty in just one part of the input data.

With this purpose, the main sources of epistemic uncertainty in the risk model can be identified and their average Indexes of Coincidence can be independently computed to identify the sources of epistemic uncertainty that have a higher influence in the decision making. According to the authors' experience, Table 2 shows reference values of average Indexes of Coincidence and what they could indicate when they are computed for a single source of uncertainty in the risk model.

Average Index of Coincidence value	Degree of influence of this source of epistemic uncertainty in measures prioritization
> 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

Table 2: Indicative meaning of average Index of Coincidence when computed for a single source of epistemic uncertainty.

Finally, Indexes of Coincidence indicate the need for epistemic uncertainty reduction measures, so they are very useful for risk-informed dam safety management. In this sense, the effect of epistemic uncertainty reduction measures in the probability distributions introduced in the risk model can be estimated and Indexes of Coincidence can be recomputed. Expected increments in average Indexes of Coincidence of more than 5% indicate effective uncertainty reduction measures, especially when Indexes of Coincidence are lower than 85%.

5. CASE STUDY

In this section, the approach introduced in this paper is applied to inform safety management in four existing concrete gravity dams in Spain. Main characteristics of these dams are summarized in Table 3. As can be observed, it is a heterogeneous group of concrete gravity dams in size and age.

Dam	Height (m)	Reservoir volume (hm^3)	Upstream slope	Downstream slope	Construction year
A	91.2	308	0.05	0.76	1956
B	31.5	0.3	0.15	0.7	1991
C	58	496	0	0.767	1960
D	59.5	24.4	0.05	0.76	1954

Table 3: Main characteristics of case study dams.

The starting point for this case study is the risk models elaborated within a first-order probabilistic risk analysis performed on each dam. The analysis made is focused on the potential sliding of these dams and the epistemic uncertainty about the foundation resistant capacity. This failure mode is analyzed since sliding produced by insufficient shear strength in the foundation is the most common cause of failure of concrete gravity dams according to the International Commission on Large Dams (38). Hence, the analysis introduced in this case study is focused on this source of epistemic uncertainty within the risk model and how it can influence decision making.

Sliding safety management in these dams deals with the prioritization of potential risk reduction measures and/or investing in reducing uncertainty about the foundation. A total number of 20 potential risk reduction measures (summarized in Table 4) have been analyzed in the four analyzed dams. These structural and non-structural measures came from a list of actions already planned by the operators to improve dam safety along with the needs revealed by the results of the risk analysis process.

Dam	Risk reduction measures	Dam	Risk reduction measures
A	1. Improve spillway gates reliability	**C**	1. Improve foundation conditions
	2. Emergency Action Plan		2. Emergency Action Plan
	3. Improve reliability of intermediate outlet gates		3. Improve reliability of spillway gates
	4. Injections to improve foundation conditions		4. Improve monitoring system
	5. New piezometers to measure uplift pressures		5. New freeboard requirements
B	1. Improve drainage system	**D**	1. Improve dam access
	2. Emergency Action Plan		2. Emergency Action Plan
	3. Improve reliability of bottom outlet gates		3. Improve drainage system
	4. Increase spillway capacity		4. Improve monitoring system
	5. Improve monitoring system		5. Remote control for spillway gates

Table 4: Analyzed risk reduction measures analyzed for case study dams.

Firstly, in order to introduce epistemic uncertainty within the risk models for this failure mode, the procedure described in (14) has been followed to obtain a family of fragility curves. In this case, since the uncertainty on the foundation resistance capacity is the main concern for the sliding failure modes in these dams, two independent random variables are considered within a Limit Equilibrium Model: friction angle and cohesion. For each dam, two probabilistic distributions have been estimated for both random variables as shown in Table 5. The estimation of these probabilistic distributions by expert judgement has been based on geotechnical in situ and laboratory tests, measurements procedures and temporal and spatial variations of results. Differences in standard deviation of epistemic uncertainty distributions between the dams indicate different levels of knowledge about the foundation.

Random variable	Mean	St. Deviation	Maximum	Minimum	Type
DAM A					
Natural uncertainty					
Friction angle (º)	50	5	65	35	Normal
Cohesion (MPa)	0.5	0.2	1.5	0.1	Log-Normal
Epistemic uncertainty					
Mean friction angle (º)	50	2.5	60	40	Normal
Mean cohesion (MPa)	0.5	0.125	1	0.2	Log-Normal
DAM B					
Natural uncertainty					
Friction angle (º)	42.3	4.1	53.5	31.3	Normal
Cohesion (MPa)	0.41	0.083	0.89	0.11	Log-Normal
Epistemic uncertainty					
Mean friction angle (º)	42.3	10.8	53.5	31.3	Normal
Mean cohesion (MPa)	0.41	0.187	0.89	0.11	Log-Normal
DAM C					
Natural uncertainty					
Friction angle (º)	42	4.2	54	30	Normal
Cohesion (MPa)	0.3	0.12	1	0.05	Log-Normal
Epistemic uncertainty					
Mean friction angle (º)	42	2.1	49	35	Normal
Mean cohesion (MPa)	0.3	0.105	0.8	0.1	Log-Normal
DAM D					
Natural uncertainty					
Friction angle (º)	40	4	50	30	Normal
Cohesion (MPa)	0.2	0.08	0.8	0.03	Log-Normal
Epistemic uncertainty					
Mean friction angle (º)	40	2	45	35	Normal
Mean cohesion (MPa)	0.2	0.07	0.5	0.05	Log-Normal

Table 5: Probability distribution considered for the random variables to obtain the family of fragility curves.

Following the procedure detailed in (14), a family of 1000 fragility curves has been obtained for each dam. For instance, Figure 7 shows the family of fragility curves obtained for dam A. As explained in Section 2, the spread of this family is an indicator of the influence of the epistemic uncertainty in the results.

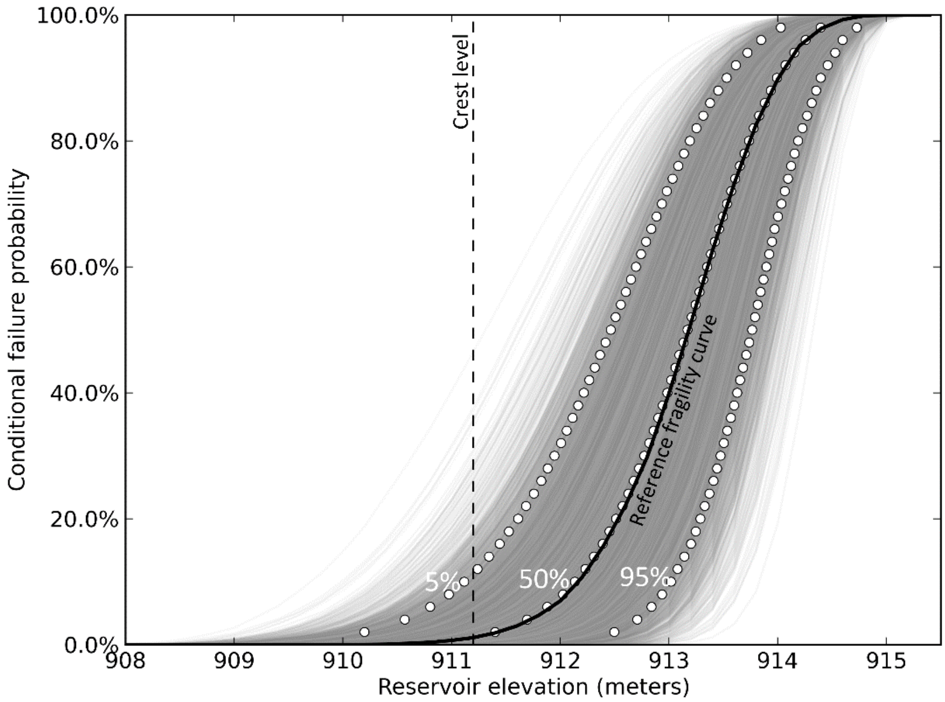

Figure 7: Family of fragility curves obtained for Dam A.

Secondly, the family of fragility curves has been introduced in the quantitative risk model elaborated for each dam in order to obtain a risk probability distribution for sliding failure. These risk models have been elaborated using iPresas Calc software (39), which is based on event trees to compute failure probability and risk. For instance, Figure 8 shows the risk model structure for Dam A. The risk model architecture of the four risk models is very similar. These risk models have been used to compute risk for the current situation and for the 20 risk reduction measures analyzed.

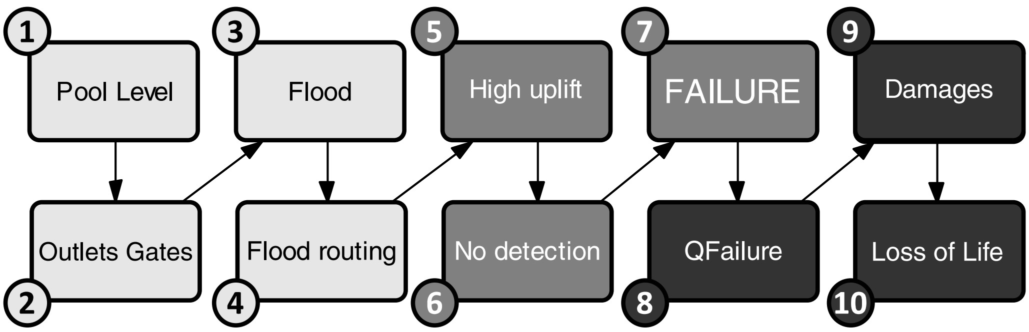

Figure 8: Risk model structure for Dam A.

In the first four nodes (nodes 1-4), this model creates an event tree to compute the probability of different flood routing scenarios in the reservoir (for different flood events, different previous pool levels in the reservoir and different cases of spillway gates availability) in order to obtain an annual exceedance probability curve of the water pool level in the reservoir. Detailed procedures followed to compute this input data are explained in (23).

Nodes 5 and 6 are different for each dam and they estimate the probability of being in different uplift pressures hypothesis, following the sliding numerical model. Probabilities introduced in these nodes are based on foundation characteristics, available information about uplift pressures and existing capacity to detect and to avoid high uplift pressures.

Node 7 is used to incorporate the sliding fragility curves in order to relate the maximum water level reached in the reservoir in each flood event with the conditional failure probability. The failure probability of each branch of the event tree is computed multiplying the probabilities of all the nodes. Consequently, when the probabilities of all the branches of this event tree are added, the dam failure probability due to sliding is obtained.

Nodes 8-10 are used to compute consequences in order to estimate risk, following equation 1. Node 8 is used to introduce a relation between the water pool level and the peak failure discharge. This relation has been previously computed using hydraulic models of the dam breach. Finally, Nodes 9 and 10 introduce the relation between failure discharge and loss of life and economic consequences due to failure. These consequences for different discharges have also been computed using a hydraulic model of the dam break flood. Detailed procedures followed to derive consequences input data are explained in (40).

For each curve of the family of fragility curves of each dam, these risk models are used to compute failure probability, economic risk and societal risk. For each dam, societal risk results have been sorted to obtain the societal risk probability distribution shown in Figure 9. As can be observed in these graphs, societal risks are higher for Dam B and Dam C, while risk variations due to epistemic uncertainty are higher for Dam A and Dam D.

Thirdly, once these risk distributions are obtained, Indexes of Coincidence proposed and described in this paper have been computed to solve the key question of this paper: Is epistemic uncertainty influencing decision making?

With this purpose, the 20 risk reduction measures analyzed have been prioritized following the procedure explained in (10), using the EWACSLS indicator (31), combining equity and efficiency principles.

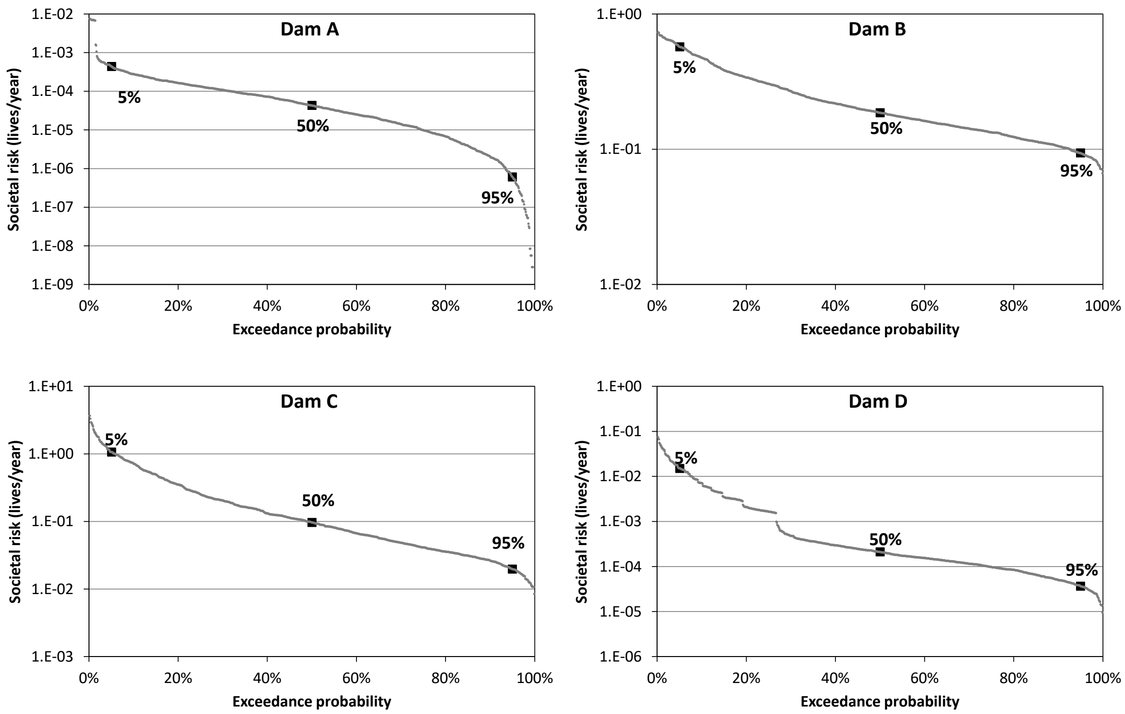

Figure 9: Societal risk probability distributions obtained for the four dams.

A reference implementation sequence of measures is obtained with the risk results obtained with the reference fragility curve in each dam. Next, 1000 implementation sequences have been obtained combining the 1000 fragility curves and their risk results obtained for each dam. These 1000 sequences are compared with the reference sequence to obtain the average Indexes of Coincidence shown in Table 6. These indexes have been computed following the equations explained in Section 4. As can be observed in this table, these indexes have been computed after prioritizing measures for each dam independently and prioritizing the 20 measures together. Figure 10 shows the variation graphs of all sequences obtained for the prioritization of the 20 measures together.

Dam	Index of Coincidence	Adjusted Index of Coincidence
A	99.35%	99.29%
B	79.86%	69.55%
C	87.42%	86.97%
D	94.11%	90.77%
All the dams	86.95%	86.60%

Table 6: Indexes of Coincidence obtained for the case study.

As can be observed, Indexes 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, Indexes of Coincidence for Dam A are close to 100%, which indicated that epistemic uncertainty has low influence on decision making. Indexes of Coincidence of Dams C and D indicate a medium influence of epistemic uncertainty on results.

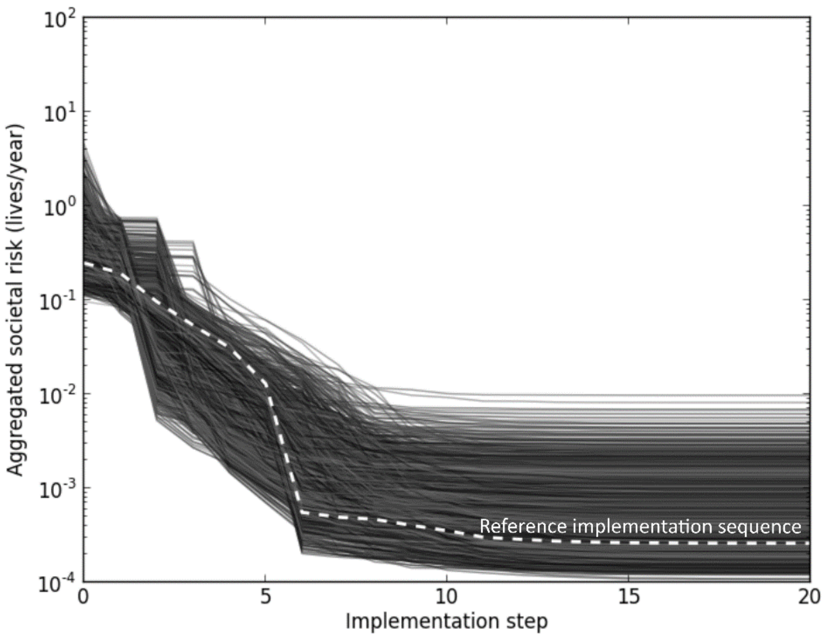

Figure 10: Variation graphs of the 1000 sequences obtained for the prioritization of the 20 measures together. Y axis represents aggregated societal risk of the four dams.

In order to check if 1000 prioritization sequences are appropriate of more computations are needed, Figure 11 illustrates results based on the number of conducted computations. Indexes of Coincidence results are stable when the number of fragility curves is higher than 500. Hence, 1000 implementation sequences seems a valid decision.

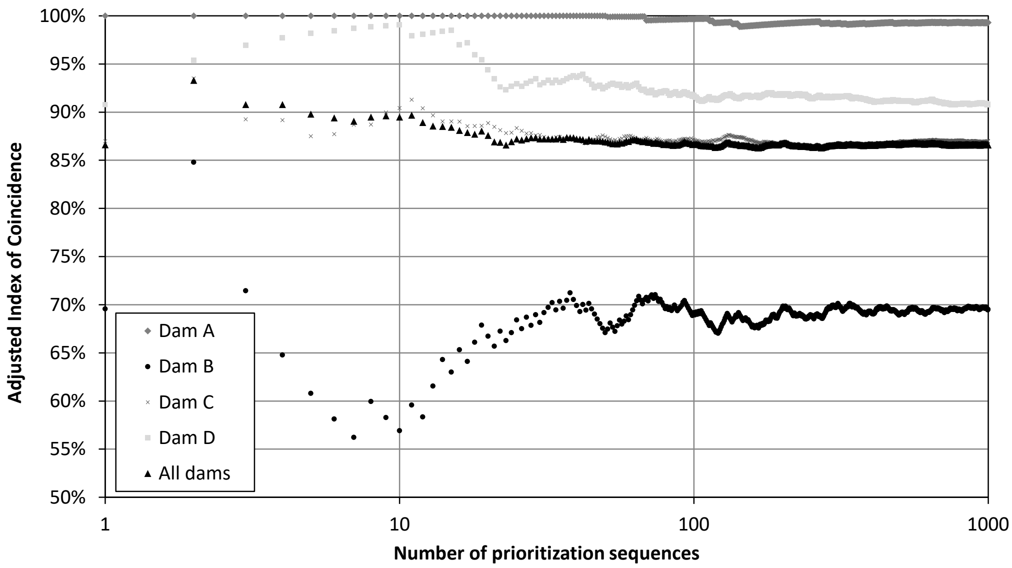

Figure 11: Influence of number of prioritization sequences in the Adjusted Indexes of Coincidence.

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 distributions shown in Table 5. In this case, the risk probability distributions shown in Figure 12 are obtained. It is obtained that reducing epistemic uncertainty has a direct effect in the steepness of probability distributions.

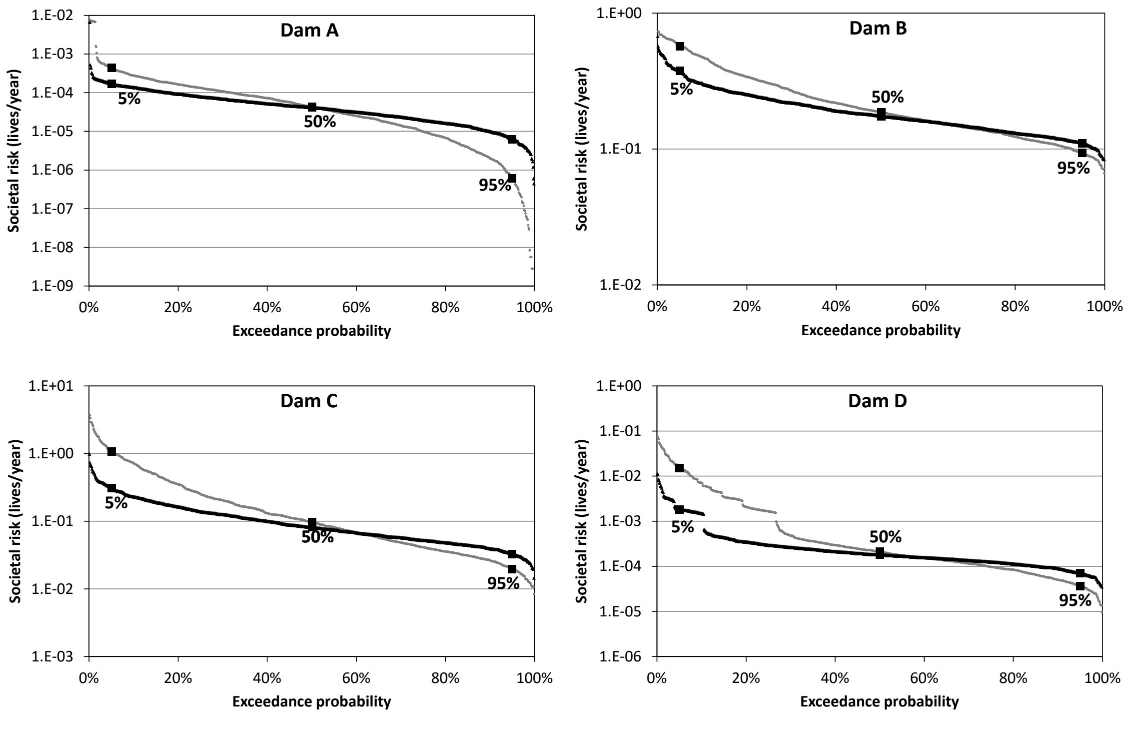

Figure 12: Societal risk probability distributions for all dams: base case (grey line) and after reducing epistemic uncertainty (black line).

Next, the same procedure has been followed to obtain 1000 sequences of risk reduction measures for each dam individually and combining them. The itineraries for the combined case are shown in Figure 13. As expected, the spread of the itineraries is lower, although it does not mean that the measures are implemented in a different order that in Figure 10.

Thus, Indexes of Coincidence have been recomputed for these cases as shown in Table 7. As can be observed the effect of reducing epistemic uncertainty in each dam has been independently analyzed in the individual sequences of each dam and in the sequences obtained combining the four dams.

Results show that reducing epistemic uncertainty in Dam C and Dam D would have a higher influence in the decision making process for the whole system of dams. In contrast, the effect of reducing epistemic uncertainty in Dam A is lower. Epistemic uncertainty reduction in Dam B has a high effect in the sequences obtained for this dam individually but its effect in the management of the four dams together is more limited. Hence, epistemic reduction actions are recommended when this dam is individually managed, but from the combined management point of view, these actions would be more recommended in Dams C and D.

If the results of reducing globally epistemic uncertainty for the four dams are analyzed, it can be concluded that these actions could be useful to support a better risk-informed decision making, since they provide an increment of Indexes of Coincidence by 4%.

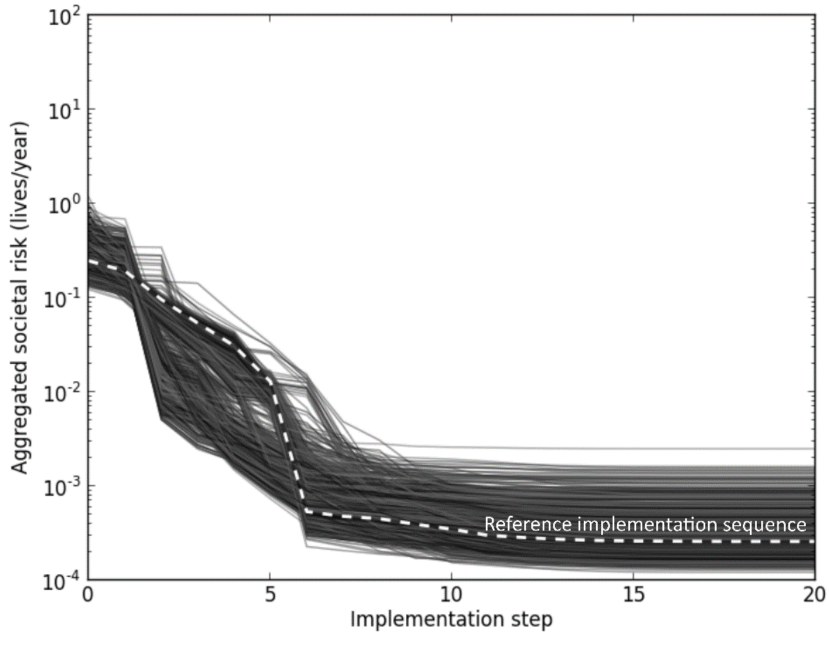

Figure 13: Variation graphs of the 1000 sequences obtained for the prioritization of the 20 measures after reducing epistemic uncertainty.

	Base case	Epistemic uncertainty reduction	Difference

Epistemic uncertainty reduction	Index of Coincidence	Adjusted Index of Coincidence	Index of Coincidence	Adjusted Index of Coincidence	Index of Coincidence	Adjusted Index of Coincidence
			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%

Table 7: Indexes of Coincidence: base case and after reducing epistemic uncertainty.

6. DISCUSSION AND CONCLUSIONS

Dams are located in natural and heterogeneous environment that cannot be controlled. For this reason, unlikely to other industries, dam safety governance deals with higher natural and epistemic uncertainties since it is directly related with the nature behavior. For this reason, epistemic uncertainty can have a higher effect on decision making, which remarks the importance of dealing with it.

This paper introduces new metrics to analyze the influence of epistemic uncertainty in decision making for dam safety. This process is based on the results of a second-order probabilistic risk analysis, which requires separating natural and epistemic uncertainty within the risk model input data. Although this is not the most common approach in the dam safety field, the distinction between both types of uncertainty takes added importance for a proper dam safety management.

These metrics are computed combining results of a second-order probabilistic risk analysis and prioritization of investments based on risk reduction indicators. The main identified discussion points about this procedure and the case study are:

- The case study introduced is focused on one source of uncertainty within the risk model: foundation resistant capacity. This approach of analyzing each source of epistemic uncertainty separately is more recommended since it allows to identify what type of epistemic reduction actions are more effective. In any case, if epistemic uncertainty is included in all the nodes of the model as explained in Section 2, Indexes of Coincidence can also be obtained although they will be lower, since the effect of different sources of epistemic uncertainty is combined.
- Hence, the introduced case study is focused on epistemic uncertainties in the second term of the risk equation: the system response, but Indexes of Coincidence can also be used to analyze the effect of epistemic uncertainty in the other terms: loads probability and consequences.
- Based on case study results, Indexes of Coincidence should be also computed for each dam individually, not only for the whole portfolio of dams. These Indexes of Coincidence are useful to identify how epistemic uncertainty is influencing decision making in each dam.
- In the case study, only one failure mode has been addressed (sliding) although in more complex cases, different failure modes could be combined. In these cases, epistemic uncertainties on the predominant failure modes will have a higher influence on the decision making.
- Even though the introduced metrics in this paper are based on risk prioritization sequences obtained with risk reduction indicators, they could also be used to compare the influence of epistemic uncertainty in other types of measures prioritization sequences.
- The effect on Indexes of Coincidence of risk reduction measures that also help to reduce epistemic uncertainty could be analyzed. For example, improvements in the surveillance and monitoring system, since they help to detect the failure modes occurrence and increase the knowledge about the dam behavior.
- Although Indexes of Coincidence have been developed within the dam safety management field, they could be also applied to analyze the effect of epistemic uncertainty in other fields. The concepts behind these indexes are equally

appropriate for other critical infrastructures, since addressing the effect of epistemic uncertainty is very important for an integrated risk management.

In conclusion, the metrics proposed in this paper have significant advantages to inform dam safety governance, since they allow measuring the effect of epistemic uncertainty in decision making. Hence, they help to identify needs for reducing gaps in dam knowledge, giving value to measures that do not have a direct effect on average risk results.

Finally, it should be remarked that the intent of the authors is dealing with uncertainty, more than fighting against uncertainty, which is identified as one of the main elements of ‘‘smart governance” (41).

As in words of (41), “All knowledge is constructed and contingent. It is, figuratively speaking, a thin layer of ice over a deep ocean filled with non-knowledge and contingent knowledge connected to contingent forms of no-knowledge. People walk on this ice, and some even dance, celebrating their splendid assets of knowledge. (. . .)” and “uncertainty is neither a menace nor a weakness but should be treated instead as a normal condition of complex decision making and governance. The task then is to find efficient ways to cope with uncertainty without destroying uncertainty’s invigorating dynamic”.

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