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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 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.

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 [2–6]. 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 [8–11,4] as shown in Fig. 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.

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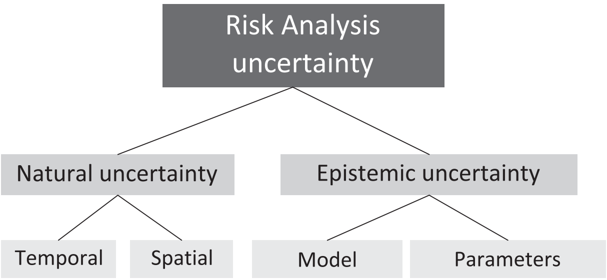

Fig. 1. Taxonomy of uncertainty in risk analysis. Adapted from [10]

- **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 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]:

$$Risk = \int P(loads) \cdot P(response|loads) \cdot C(loads, response) \quad (1)$$

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 Fig. 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.

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