Seismic Risk of a Co-Located Portfolio of Dams – Effects of Correlation and Uncertainty

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ABSTRACT: This paper looks at issues associated with estimating risk of seismically initiated failure (uncontrolled release of the reservoir) of dams that are co-located with respect to each other and the location of future earthquakes. These may be dams on the same river or dams regionally co-located on different rivers. Failure of one or more dams could lead to serial dam failures on a single river; or produce regional consequences on multiple rivers. With the increased interest in the use of risk-based methods to evaluate the safety of dams, this paper looks at the effect of sources of correlation or dependence on the risk to a portfolio of co-located dam projects. Results of a parametric study that evaluates a number of these factors are described. The consequences of a seismic event are not limited to dam failure and downstream inundation. Since it is far more likely that dams may be damaged (as opposed to failing) during a seismic event, these 'other' consequences include loss of function (i.e., hydropower production, water supply, etc.) as reservoirs may need to be lowered following the earthquake.

1 INTRODUCTION

1.1 *Background*

For more than three decades there has been a slow, but growing interest in the use of risk analysis methods to evaluate the performance and safety of dams. Although risk analysis has not yet become a standard-of-practice within the dam engineering community, in other areas of civil engineering it is well practiced; business applications (decision-making, insurance), emergency management, and regulatory environments. In the hydropower industry in the U.S., the Federal Energy Regulatory Commission (FERC) has committed to integrating risk-informed decision making into its dam safety program by 2014 (FERC, 2009). This action by the FERC and continuing efforts of the U.S. Bureau of Reclamation, the U.S. Army Corps of Engineers, ICOLD, among others suggests increasing momentum with respect to the use of risk-based methods in dam safety.

1.2 *Focus of this Paper*

The subject of seismic performance for dams has been a topic of considerable interest in the U.S. since the failure of the Sheffield Dam in 1925. This interest was further heightened by the embankment failure of the Lower San Fernando Dam and the threatened, uncontrolled release of the reservoir in 1971. For the case of large earthquakes **M** >7 which can cause high ground motions in a large region, hundreds to possibly thousands of dams may simultaneously experience high seismic loading and thus a potential for damage or failure in a region. For instance, following the 1989 **M** 6.9 Loma Prieta earthquake in California, the Division of Safety of Dams required that more than 120 dams be inspected. As a result of the Sichuan **M** 7.9 earthquake in Peoples Republic of China, thousands of dams experienced strong ground motion.

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This paper examines a particular aspect of seismic risk analysis for a portfolio of dams - the effects of correlations of ground motion and probabilistic dependence associated with aleatory as well as epistemic uncertainties on estimates of risk for a group of dams. As we will show, correlations with respect to the characterization of the seismic hazard can have important implications with regard to the performance of dams and the potential for significant regional impacts. The subject of correlation and sources of dependence in seismic risk analysis is not new. Reed, et al. (1985) addressed within-facility correlation issues, whereas Park, et al. (2007) addressed these subjects for an insurance portfolio of conventional structures.

2 UNCERTAINTY AND CORRELATION

A primary purpose of a risk analysis is to identify and model the sources of uncertainty that affect the analysis and the quantification of the likelihood of future events of interest (e.g., uncontrolled release of the reservoir). With respect to seismic risk analysis of dams, there are a number of sources of uncertainty associated with estimating the likelihood of future earthquakes and seismic loading and in estimating the performance of dams. If one broadens consideration of a risk analysis from a single dam system (located geographically at a point) to a portfolio where the dams are co-located with respect to each other and the earthquake source, there are other factors and sources of uncertainty that introduce sources of dependence and correlation which are important considerations when estimating the seismic risk to the portfolio and to the region that may be affected by failures within the portfolio.

2.1 *Types Uncertainty*

Engineers are model builders, whether they are physical or analytical/numerical (computer) models that are used to understand and ultimately predict the performance of a system, assess its safety, etc. By their nature, models are a representation of reality and are driven by the parameters that must be specified by the user (i.e., geometry, mass, material constitutive properties, etc.).

Within the context of models and their parameters, there are two types of uncertainty defined: aleatory and epistemic uncertainty. The first, aleatory uncertainty is attributed to the inherent randomness of events or properties. These events are predicted in terms of their frequency of occurrence or the fraction of the time an event or property (i.e., material strength) is realized.

Epistemic or knowledge-based uncertainty is attributed to lack-of-knowledge about events, or physical processes that limit the ability to model events of interest. A second type of knowledge uncertainty is attributed to limitations in available data (amount and quality) that impacts the assessment of model parameters (parametric epistemic uncertainty). When data are limited, parameter estimates may be quite uncertain (i.e., statistical confidence intervals on parameter estimates are large).

To systematically identify and assess uncertainties it is useful to construct a framework or taxonomy to partition the types of uncertainty in terms of their effect on models and estimates of model parameters. Table 1 shows the taxonomy for characterizing the sources of uncertainty and their type in the context of models and model parameters. The framework in Table 1 has a number of benefits in developing and quantifying a risk model. First, it offers a guide to insuring that all sources of uncertainty are identified. Second, it supports the characterization of uncertainties as aleatory or epistemic, which for many problems may be difficult to assess. Lastly, a clear framework and accounting of sources of uncertainty avoids double counting or failing to identify and count uncertainties.

Noteworthy in Table 1 is the fact there are two, very different, types/sources of uncertainty that have a systematic effect on modeling estimates; model-epistemic and parametric-aleatory. Both of these types of uncertainty have different and important impacts on seismic risk estimates for a co-located portfolio of dams.

2.2 *Sources of Dependence and Correlations*

Given a portfolio of dams that are spatially co-located with respect to each other and the location of future earthquakes, there are a number of sources of correlation and dependence that should be addressed in a seismic risk analysis. The sources of correlation and dependence addressed in this paper are:

Table 1. Taxonomy / partitioning of uncertainties

Element	Epistemic	Aleatory
Modeling	Uncertainty about a model and the degree to which it can predict events. Model, epistemic uncertainty addresses the possibility that a model may systematically (but not necessarily predictably), over- or under-predict events/results of interest (i.e., deformations).	Aleatory modeling variability is the variation not explained by a model. For instance, it is variability that is attributed to elements of the physical process that are not modeled and, therefore, represents variability (random differences) between model predictions and observations.
Parametric	Parametric epistemic uncertainty is associated with the estimate of model parameters given available data, indirect measurements, etc.	This uncertainty is similar to aleatory modeling uncertainty. However, this is variability that may be due to factors that are random, but have a systematic effect on model results.

- PSHA Model, Epistemic Uncertainties – In a probabilistic seismic hazard analysis (PSHA), there are a number of sources of model epistemic uncertainties that are explicitly modeled (SSHAC, 1997).
- Parametric, Aleatory Uncertainty – There are random (aleatory uncertainty), but systematic differences between earthquakes of a given magnitude. These differences have a pronounced effect on the level of ground shaking that is generated from one event to the next.
- Model, Aleatory Uncertainty – In the region near an earthquake, the spatial field of ground motions are correlated. For sites close to one another (with a few kilometers), ground motions are very similar and this highly correlated.

The first of these sources of correlation or dependence has to do with the sources of model uncertainty in a PSHA. The current standard of practice in conducting a PSHA is to explicitly model the sources of model uncertainty in the seismic source characterization and the ground motion modeling parts of the analysis through the use of logic trees (SSHAC, 1997). Each seismic hazard estimate that is represented on a logic tree branch (a path through a logic tree), corresponds to a model of the aleatory rate of occurrence of earthquake ground motions. Different aleatory models of the earthquake hazard differ in terms of the level shape of the hazard curve due to different models (ground motion models, earthquake recurrence models, etc.) that are used. Figure 1 shows a schematic illustration of the difference in seismic hazard estimates as derived from different models in a PSHA. Associated with each curve is a weight (that is derived from the PSHA logic tree) that is a measure of the degree to which it is supported by the current state-of-knowledge.

Empirical evaluation of ground motion suggests the residuals with respect to a best estimate can be represented by,

$$\varepsilon_{ij} = \tau_i + \varsigma_{ij} \tag{1}$$

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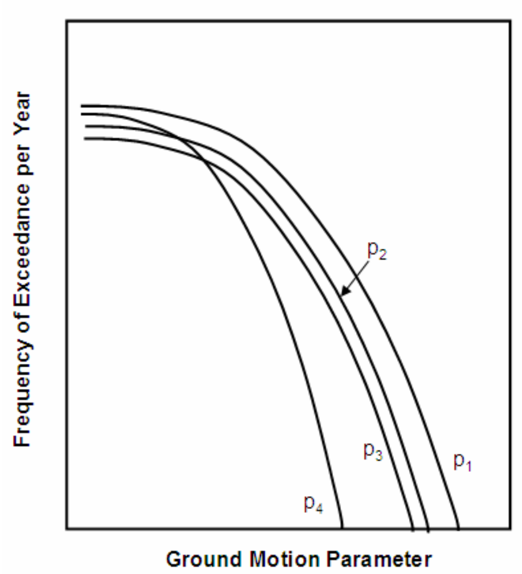

Figure 1 Schematic illustration of the model, epistemic uncertainty in PSHA results for a site.

where, ε_{ij} = deviation for the jth strong motion recoding (at an individual recording station) due to the ith earthquake; τ_i = event term for the ith earthquake; ς_{ij} = intra-event variability for the jth strong motion recoding (at an individual recording station) due to the ith earthquake.

The total logarithmic standard deviation of ground motion residuals (of the ε_{ij}'s is approximately 0.60 (Chou and Youngs, 2008) which produces a +/- two standard deviation range of approximately 11. The logarithmic standard deviation of the event terms (the τ_i's) is approximately 0.31 and the intra-event variability is approximately 0.51.

The inter-event variability is a source of parametric aleatory uncertainty that has a random, but systematic difference between earthquakes of the same magnitude. The inter-event term is attributable to random differences between earthquakes (i.e., stress drop), where the ground motions are earthquake systematically different from the average trend across all earthquakes. These event-to-event terms (so-called tau effect) differences are shown graphically in Figure 2. In terms of evaluating the seismic risk for a portfolio of dams, the tau effect says that ground motions at all sites may be systematically higher or lower for a given earthquake.

The last source of correlation addressed is associated with the random field of model, aleatory uncertainty. Within the spatial field of ground motions that is produced by an earthquake, studies have evaluated the correlation between sites as a function of their separation distance. Figure 3 shows an estimate of the correlation coefficient for ground motions estimated by Boore, et al. (2004). For spatially co-located systems with relatively small separation distances (<5km, the correlation coefficient is greater than 0.5 indicating that if the ground motions at one site are high, there is a good likelihood that motions at nearby sites is also high. Similarly, if motions are low, they are likely low at nearby sites.

3 DAM PORTFOLIOS AND EARTHQUAKES

There are a number of circumstances where the performance of a portfolio of dams during a seismic event can be a focus of interest. The simplest of course is the general concern that multiple dams may be damaged or fail during or soon after an earthquake. Because the failure of dam(s) can compound the impact an earthquake has on a region, a realistic measure of the likelihood of such an occurrence is important. There are two cases that are looked at in this paper:

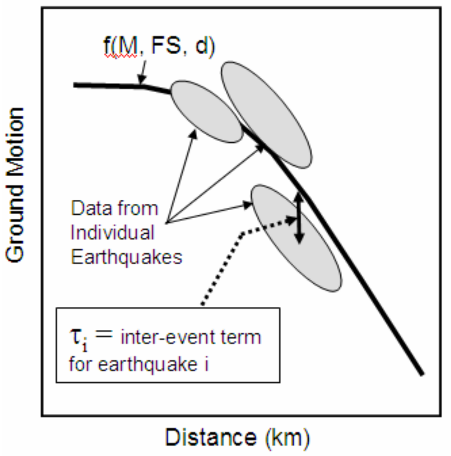

Figure 2 Illustration of the inter-event variability in earthquake ground motions.

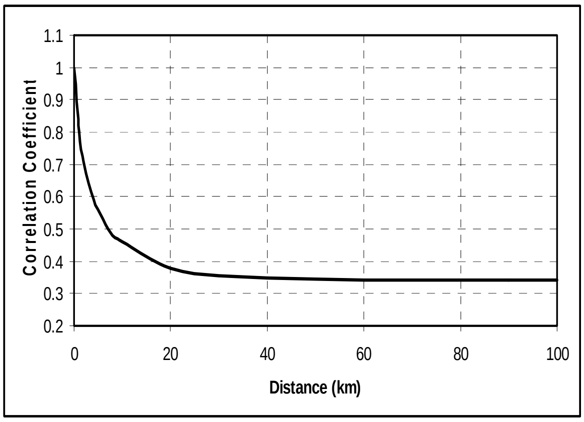

Figure 3 Correlation coefficient for earthquake ground motions as a function of distance (Boore, et al., 2004).

- Dams on the same river where failure of one or more upstream dam could affect the performance of other dams downstream, and/or
- Dams located on different rivers (simply a group of dams located in the vicinity of an earthquake.

While the focus of this work is to evaluate the effect of different sources of correlation on the likelihood of dam failures, it is useful to identify the potential consequences associated with the different cases.[1] For instance, in case one (multiple dams on the same river), the consequences of one or more seismically initiated dam failures could in downstream consequences (due to the dam break floods), further downstream dam failures as a result of the dam break inflow and potential for overtopping failures, and loss of function of the failed projects (i.e., hydropower production, water supply, flood control, etc.). With multiple dams on the same river, the likelihood of dam failure related consequences is higher than if there was only one dam. The focus of this paper is to assess this potential and the effect of different sources of correlation on the results.

In the second case with multiple dams located on different rivers, the impact of multiple dam failures could potentially be more widespread from the simple perspective there could be consequences experienced in multiple parts of the region as opposed to the first case where the dam failure consequences would be restricted to the inundation along one river. Again, this second case, the issue addressed in the analysis is the effect different sources of correlation could have.

4 OBSERVATIONS

This paper has described sources of uncertainty and correlation that have varying and important effects on an assessment of the likelihood of multiple dam failures that are co-located with respect to each other and the occurrence of moderate to large magnitude earthquakes. These sources of correlation, which are associated with aleatory and epistemic sources of uncertainty, have a systematic effect on seismic risk estimates for co-located facilities.

The results of the seismic risk calculations for the two cases that were evaluated suggest the epistemic uncertainty in the seismic hazard analysis (ground motion and seismic source characterization) is the largest, consistently important contributor to the potential seismic risk in both cases. Uncertainties in the seismic hazard are important from two perspectives; the estimated

[1] Note, in this paper the details of dam failure inundation and the effect on downstream dams is not addressed. Therefore, the discussion of the potential consequences of dam failures is presented in general terms only.

frequency of dam failures (may be higher or lower) and the uncertainty in seismic risk estimates.

The systematic effect of aleatory, parameter uncertainty is an important contributor to estimates of the seismic risk of multiple dam failures. This effect increases the likelihood for multiple dam failures and at the same time it increases the likelihood of cases where no or few dam failures occur. The importance of the spatial variability in ground motions is important, but limited to those cases when dams are relatively close to each other (i.e., within 20 km).

It is important to recognize that historically, the performance of dams exposed to strong ground motions world-wide has been quite good. While failures have occurred (i.e., Sheffield Dam in California, 1925) and dams have been damaged, some significantly (Lower San Fernando Dam during the 1971 earthquake), the overall performance record has been good. At the same time however, the engineering profession have used and relied on engineering analytical tools (i.e., non-linear dynamic finite element analysis) to estimate the expected seismic performance of dams for given (say deterministically determined levels of ground shaking) and have concluded that damage or dam breach may occur, thus leading to decisions that seismic safety modifications are required. These same analytical models are of course used to make seismic fragility estimates of dams. As a result, the dichotomy between analytical predictions and field experience is one that needs to be addressed in the future to improve estimates of seismic performance and risk.

5. REFERENCES

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