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Support vector machine based reliability analysis of concrete dams

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ABSTRACT

This paper presents possible combination of structural responses of concrete dams with machine learning techniques. Support vector machine (SVM) method is adopted and two broad applications are presented: one for a simplified flood reliability assessment of gravity dams and the other for detailed nonlinear seismic finite element method (FEM) based analysis. Up to seventeen random variables are considered in the former example and the results of SVM contrasted with classical reliability analyses techniques (i.e., first- and second-order reliability methods, Monte Carlo simulation, Latin Hypercube and importance sampling techniques). For the latter example, a FEM-SVM based hybrid methodology is proposed for reduction of number of nonlinear analyses. A discussion is provided on the relation between the optimal earthquake intensity measures, the damage states and the accuracy of prediction. It is found that the family of SVM (i.e. standard, least squares, multi-class and regression) is an useful and effective tool for classification, response prediction and reliability analysis of the concrete dams with reasonable accuracy.

1. Introduction

1.1. Transition from deterministic to probabilistic methods

Traditionally in structural and geotechnical engineering, the structural safety has been evaluated based on deterministic factor of safety (FS), defined as the ratio between the average resistance, R (i.e., capacity), the maximum load under which a system can perform its intended function, and the average stress, S (i.e., applied load or demand) [109]:

$$FS = \frac{R}{S} \tag{1}$$

If $FS > 1$, a margin of safety exists. Here, the fundamental concept is to design the structure with appropriate safety margin, so that any source of embedded uncertainty either in the demand or the capacity do not threaten to cause failure [33]. Based on Ruggeri [101], the most well-consolidated traditional method for deterministic safety assessment of concrete dams is limit equilibrium method (LEM) in which the dam is assumed to be a rigid body and the sliding is only allowed along the critical surfaces (i.e., concrete-rock interface and concrete lift joints). This method which is followed by many regulators/countries is mainly based on experiences and engineering judgment [114]. Generally, many of these factors of safety have the following form:

$$FS = f(T, W, U, \varphi, c, A, \alpha, FS_{\varphi}, FS_c) \tag{2}$$

where T is shear force, W is the weight, U is uplift force, φ and c are angle of friction and cohesion at the considered plane respectively, A is the area of rapture, α is the inclination of the sliding with respect to horizon and finally, $FS_{\varphi} \geq 1$ and $FS_c \geq 1$ are the partial factor of safeties with respect to friction and cohesion, respectively.

The advantage of this method is that the expression for (sliding) safety factor is straightforward; however, they have not been calibrated against a useful safety level [61]. A larger factor of safety does not necessarily imply a smaller risk, because its effect can be canceled out by the larger uncertainties in the design [112]. This method uses the identical threshold factor of safety value for a given failure mode without accounting for the degree of uncertainty involved in the calculation [101].

Then, the margin of safety, Z, can be defined (it is the difference between resistance and stress as oppose to FS which was the ratio between those two):

$$Z = R - S \tag{3}$$

If capacity exceeds demand, $Z > 0$, the system is in a survival state. If demand exceeds capacity, $Z < 0$, the system is in a failure state. The condition $Z = 0$ is the limiting state. This function, Eq. (3), is known as limit state (LS) equation or performance function. For example, the following simple LSs can be defined for a typical gravity dam:

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$$Z_1 = (W-U).\ \tan\varphi + c.A - T$$
$$Z_2 = \sum_{i=1}^{n} (F_R.\ d_R)_i - \sum_{j=1}^{m} (F_S.\ d_S)_j \tag{4}$$

where F_R and F_S are resisting and driving forces, respectively; and d_R and d_S are the corresponding moment arms around the dam's toe [129].

Consequently, the failure probability may be computed as the probability of having $Z < 0$. "Structural reliability" analysis deals with the quantitative assessment of the failure probability, given a model of the uncertainty in the structural, environmental and load parameters [76]. The reliability estimated as a measure of the structural safety can be used in a decision process. For example, a lower level of the reliability can be used as a constraint in optimization problems [113]. In order to estimate the structural reliability using the probabilistic concepts it is necessary to include the uncertainty [31] and random variables (RVs) in the problem definition.

1.2. Objectives and organization

Based on an extensive literature review in Section 1.3, there is no comprehensive research on structural reliability and estimation of failure probability in concrete dams using the support vector machine technique. This paper aims to adopt SVM to determine the failure probability of the gravity dams under material, modeling and loading uncertainties.

The main innovation of this research can be summarized as follows:

- Combination of structural reliability and SVM for the first time in response analysis of concrete dams.
- Contrasting both the simple analytical technique and complex finite element method in SVM based reliability analysis.
- First application of seismic reliability analysis of concrete dams which accounts for ground motion record-to-record variability.
- Simulation of the system reliability under both the hydrological hazard (analytical model) and seismic hazard (finite element model).
- Proposing a hybrid FEM-SVM based methodology for seismic reliability assessment of dams.

First, the fundamental theory of structural reliability (Section 2) as well as the concept of support vector machine (Section 3) are reviewed. Next, two applications are discussed: 1) a simplified gravity dam model based on LEM theory accounting for the material uncertainty and flood loading, and 2) a finite element model of the couple dam-foundation-reservoir system with fracture mechanics based interface joint subjected to large number of real ground motions (Section 4). Results are discussed in Section 5 and the summary and future work will end the paper (Section 6).

1.3. Comprehensive literature review

This subsection provides a comprehensive literature review on the subject studied. Considering that the present paper aims to combine three concepts, i.e., 1) structural reliability, 2) support vector machine (SVM), and 3) concrete dam engineering, one-to-one relationship between these three concepts are reviewed separately as it is schematically shown in Fig. 1. Then, the objectives of this paper are explained.

The mathematical definition of reliability is different from fragility (while they can be connected in some aspects). Readers interested in fragility analysis of concrete dams may refer to Hariri-Ardebili and Saouma [45] where up to 25 research studies carried out between 1998 and 2016 worldwide are summarized. Nearly all of these publications are limited to seismic fragility curves and surfaces where the probability of failure (or any intermediate limit state) is computed as a function (usually in the form of log-normal CDF) [121] of ground motion intensity measure, e.g. peak ground acceleration (PGA) or the structure's first-mode spectral acceleration ($S_a(T_1)$) [73].

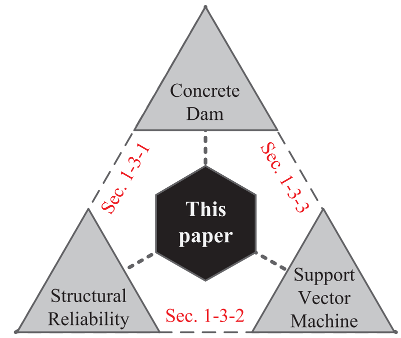

Fig. 1. Skeleton of the literature survey and the relation between the studied concepts.

1.3.1. Reliability analysis of concrete dams

To the best of the author's knowledge Bury and Kreuzer [15] is the first work on calculation of the failure probability in concrete dams. They made rigid body analysis of a gravity dam under sliding failure mode. Gumbel distributional model was assumed for both the annual peak flood and the ground acceleration.

Baylosis and Bennett [8] evaluated the safety and failure probability of a high gravity dam under the static and dynamic conditions. Three failure modes were considered (i.e., sliding, overturning and overstressing) and reported that probability of sliding during earthquake is negligible compared to two others.

These two were followed by de Araújo and Awruch [29] where both the concrete properties and the seismic excitation were assumed to be RVs in finite element analyses. Safety factor against sliding, concrete cracking and crushing were computed using Monte Carlo simulation (MCS) and presented as a cumulative probability.

Horyna [49] is the first solid research on the application of structural reliability in the concrete dam assessment. He focused on post-crack dynamic analysis of existing gravity dams and evaluated the reliability against sliding. Both the analytical and experimental studies were performed. The ground motion type, PGA and water level were assumed to be three main RVs in the reliability assessment.

Jeppsson [54] performed a safety assessment of a concrete column in an existing dam using both the current Swedish deterministic guideline and reliability analysis. Overturning and sliding were considered as two limit states. Reliability index was computed as a function of coefficient of variation (COV) in the RVs (e.g., uplift pressure, ice load, and angle of friction).

Kazemi [58] compared the safety levels resulting from conventional seismic stability analysis (allowable stress method) of a typical concrete gravity block subjected to pseudo-static earthquake load and the ultimate limit state design principle (reliability method). A dam monolith with and without post-tensioned anchors was considered. He found that while some measure of safety is ensured by following the conventional approach, reliability method provides a consistent level of structural reliability in the stability analysis of dams.

Saouma [105] combined the concept of reliability index (through the point estimate method and Taylor's series finite difference estimation) with finite element fracture mechanics to determine the safety index after rehabilitation. Linear elastic fracture mechanics (LEFM) was used for evaluation of the original dam while nonlinear fracture mechanics (NLFM) was adapted for the retrofitted one. Reservoir elevation, fracture toughness, cohesion and friction angle were taken as normally distributed RVs. He mentioned that the comparison between two methods is not possible since input data and analysis types are different.

Carvajal et al. [18], Carvajal et al. [17] and Carvajal et al. [16] performed reliability analysis of a gravity RCC dam by MCS and first order reliability method (FORM). The shear parameters are evaluated using an intrinsic curve formula and the variability is evaluated from variability of compressive and tensile strength. Statistical analysis of

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