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Combining Monte Carlo and finite difference methods for effective simulation of dam behavior

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ABSTRACT

Monte Carlo simulation provides a probabilistic approach to evaluate the physical behavior of infrastructures. Therefore, the performance could be achieved in a more realistic manner. Within this framework, an innovative software code is developed by combining the Monte Carlo and finite difference methods to predict the behavior of embankment dams after impounding. In order to assess the efficiency of the method, the case study of Chahnimeh-4 dam, located at Southeast of Iran, has been investigated in detail. The behavior of this dam is predicted and compared with the field monitoring by using the Kolmogorov–Smirnov test. The results indicate the robustness of the proposed method and it can be then efficiently used in monitoring the dam responses with respect to the various factors like seepage, piping and settlement.

1. Introduction

Water reservoirs provide significant social and economic benefits, however risks made by the unstable dams could threat the life and property of the people who live in the downstream area. The safety assessment of a dam is a complex issue that needs to be analyzed and evaluated comprehensively by using different softwares. Therefore, it is required to analyze the monitoring information, which is a key subject in the field of dam engineering. A typical dam contains various types of piezometers as total stress cells, settlement devices, triaxial deformation tubes, inclinometers and extensometers, all are installed during construction [1]. These sensors face uncertain inputs, which are originated from the physical uncertainties and human errors. It can be expected that the combination of these unknown parameters leads to an unreliable design [2]. Uncertainty analysis by mathematical and statistical softwares can be then used to evaluate the risks. Fig. 1 explains the process of risk analysis for a dam. Other uncertain events affecting dam's behavior and then its modeling are water inflow, reservoir level, earthquake magnitude and etc. They are used as input to the uncertain models, leading to probability distribution of response values (deformation, stresses, etc.). These consequences are expressed as the probability of occurrence functions. In this process, dam safety can be then assessed by mathematical models using the monitoring data [3].

Monte Carlo simulation is a very useful approach for modeling the problems with uncertainty in the inputs. This simulation method is based on input parameters those reflect the probability density function (PDF) of each parameter. Thus, the repetitive calculations take into account the randomly selected combinations of the inputs, generating a PDF or cumulative density function (CDF) for the outputs. Based on these CDFs, a risk level representing the high end (e.g. 95%), central tendency (median or mean), or any other desired level of probability can be obtained [5].

For the first time, Kim and Major [6] used Monte Carlo to simulate the behavior of soil parameters as uncorrelated random variables. In recent years, Lohr and Mueller [7] used Monte Carlo simulation in generating the flood hydrographs. This procedure provides a distribution function of maximum reservoir levels as a basis for assessing the probability of dam failure. Based on the monitoring data, ZhongRu et al. [8] proposed a risk degree by combining the Bayesian approach and field monitoring data. This five-grade risk degree is used to evaluate the safety conditions of dams. Froehlich [9] applied Monte Carlo simulation to estimate the degree of uncertainty in the predicted peak flows and water levels in downstream of a breached embankment dams. Yanmaz and Gunindi [10] performed a probabilistic reservoir routing based on the Monte Carlo simulation to compute the maximum reservoir

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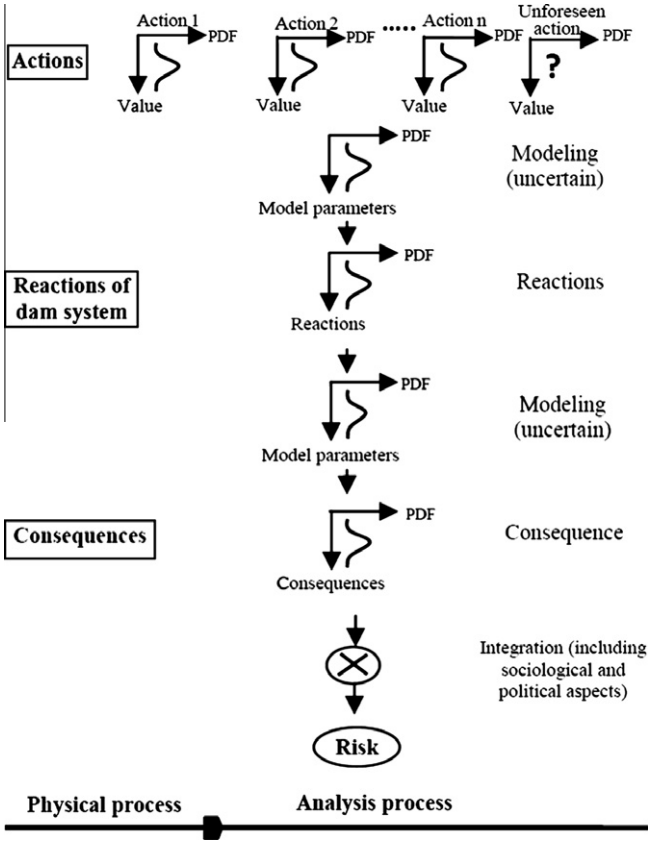

Fig. 1. Risk assessment processes in a dam [4].

elevation and overtopping reliability. Calvo and Savi [11] proposed a method for the formal risk analysis in debris flow-prone areas. To quantify debris flow risk, a Monte Carlo procedure is applied that randomly selects the input variables of mathematical models. Ahmed [12] investigated the unconfined flow through dams by modeling the hydraulic conductivity with lognormal distribution. He then compared the estimated flow quantity by using the stochastic approach with the observed ones. Alkasawneh et al. [13] studied the effect of different slip surface search techniques on the safety factors, obtained by using the slope stability methods. They compared results obtained by using the finite element (linear grid and rectangular grid) and the Monte Carlo methods. The results showed that the limit equilibrium methods will improve when coupled with the Monte Carlo approach.

Therefore, combining the numerical models and the Monte Carlo simulation technique could be an appropriate option for the reliability analysis. This study introduces an innovative approach by using the Monte Carlo simulation and the numerical analysis of the finite difference [14–16] to predict the behavior of dams with respect to the different types of loadings. In Section 2, the methodology of study will be explained. In Section 3, a real case study concerning the dam behavior is described and then in Section 4 the results of applying the methodology on the case study are evaluated. Finally, Section 5 concludes the paper.

2. Methodology

Dam behavior is conventionally evaluated by models of deformation, seepage, stress, and crack opening by using the complex and nonlinear functions [17]. As the consequences of dam failure are serious, monitoring the behavior of dams is needed in the early stages of the impounding. It is also important to validate the assumptions made at the design step, particularly to control seepage phenomenon. Therefore, long-term monitoring of dam performance and regular measurements are improved during the operation period to ensure that the dam structure is functioning well [1]. If the results of monitoring are in good consistency with the model estimations, it shows that the method of analysis has been carried out in a practical manner.

Monte Carlo and other probabilistic analytical techniques are relatively straightforward when applied to a case with parameter variability, the natural heterogeneity of a system and also parameter uncertainty. On the other hand, model uncertainty represents a lack of knowledge concerning variables and their interactions to each other and thus constitutes uncertainty about whether a model approximates a real-world process or not [5]. In brief, the Monte Carlo simulation is a numerical method to solve problems through stochastic simulation, and in this research the framework of study can be explained as follows:

(a) The values of each stochastic variable are generated. The generations are based on the lognormal distribution for permeability variable [12,18,19] and the normal distribution for density of foundation soil [20–22].
(b) The pore pressures are obtained by using the finite difference model.
(c) The steps described in points (a) and (b) are repeated until a statistically valid numbers of pore pressures are obtained.
(d) The statistics of pore pressures are obtained like the mean, variance, CDFs and PDFs.
(e) Finally, the results of Monte Carlo finite difference simulation and those of the monitoring are compared to figure out how the predication is correlated with the real observations.

To run the probabilistic analysis, a new code is developed to work interactively with FLAC (Fast Lagrangian Analysis of Continua, Itasca) [23]. FLAC is a dominant two-dimensional continuum software for modeling the behavior of the soil, rock and other structures and their interaction with water, and it can be used interactively or in the batch mode. The governing equation of FLAC are as follows. The fluid transport is described by Darcy's law:

$$q_i = -m_{ij}k(s)\frac{\partial}{\partial x_i}(P - \rho_w g x) \tag{1}$$

where q_i is the specific discharge vector, m_{ij} is the mobility coefficient, $k(s)$ is the relative permeability as a function of the saturation s, P is the fluid pressure, ρ_w is the density of fluid, and g is the gravity value. For saturated/unsaturated flow, the air pressure is assumed zero. The fluid mass balance relation is

$$\frac{\partial \lambda}{\partial t} = -\frac{\partial q_i}{\partial x_i} + q_v \tag{2}$$

where λ is the variation of fluid content in time t, and q_v is the volumetric fluid source intensity. The balance of momentum has the form

$$\frac{\partial \sigma_{ij}}{\partial x_j} + \rho g = \rho \frac{du_i}{dt} \tag{3}$$

where $\rho = (1 - n)\rho_s + n\rho_w$ is the solid bulk density; ρ_s and ρ_w are the densities of the solid and fluid phase, respectively, and n is porosity.

The new developed code in this study, provides the FLAC software with desired PDFs of the input variables, invokes the software to calculate the different adapted phases, and finally collects the outputs. In fact, along with each variation in soil parameters, a new problem is defined and then solved. According to the