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Reliability analysis of embankment dam sliding stability using the sparse polynomial chaos expansion

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ABSTRACT

A probabilistic stability analysis of an embankment dam using in-situ measurements is presented in the paper. Three soil properties, including the dry density (γ_d), the effective cohesion (C') and the friction angle (ϕ') are simulated by means of random variables based on in-situ measurements or laboratory test results, to consider the soil variability. Concerning the deterministic calculations, two models are developed in the study. The first one is a numerical model based on the finite difference method, and the second one is an analytical model based on the limit equilibrium method. For the latter, a two-step Genetic Algorithm (GA) is proposed to locate the best noncircular critical slip surface. These two models are both used for the safety factor evaluation of the studied dam and compared in a probabilistic framework in terms of safety factor distribution and failure probability. The employed reliability method for the probabilistic analysis is the Sparse Polynomial Chaos Expansion (SPCE). The failure probability and the safety factor distribution of the considered dam under normal exploitation conditions and seismic loading conditions are presented. The influence of the random variable distribution type on the probabilistic results is studied. In addition, a PCE-based Global Sensitivity Analysis (GSA) is embedded in order to investigate the contribution of each variable to the safety factor variance.

1. Introduction

It is commonly recognized that the inherent variability of soil properties is important in embankment dam engineering since these structures are mainly made of natural materials such as earth or rock-filled materials. For this reason, it is of high interest to study the embankment dam stability in a probabilistic framework, in order to take into account the uncertainties related to the soil variability.

For embankment dams, large quantities of geotechnical data are usually available in several phases: design studies, construction controls and monitoring measurement [1]. These data are still not well exploited for the reliability of embankment dams, although some authors have underlined the benefits of carrying out a statistical analysis on them [2,3]. For example, Smith and Konrad [2] provided essential insights into the assessment of the hydraulic conductivity of an embankment dam, by analyzing the spatial continuity of the measured fines content during the construction.

Concerning the reliability analysis of embankment dam stability, several studies can be found in the literature. Liang et al. [4] developed a probabilistic model for assessing the reliability index of multi-layered embankment dams. The performance function and the reliability index are derived by the First Order Second Moment (FOSM) with a modified Fellenius method. Gaouar [5] studied the reliability of hypothetical earth dams using random fields of undrained shear strength. Peyras et al. [6] developed a semi-probabilistic method for embankment hydraulic works applied to sliding mechanism. Babu and Srivastava [7] carried out a probabilistic stability analysis for four rehabilitated earth dams using the Response Surface Method (RSM) in combination with the First Order Reliability Method (FORM) and a numerical model. Carvajal et al. [8] developed a probabilistic modelling of Roller-Compacted Concrete embankment gravity dams using the shear strength limit state by FORM and Monte Carlo (MC) simulations. Yi et al. [9] proposed a new program 3DSTAB combining slope stability analysis and reliability analysis for a rock-filled dam. The limit equilibrium method was used to calculate the safety factor of the critical slip surface. Mouyeaux et al. [3] studied the variability of the safety factor of a well-documented embankment dam, using the Monte Carlo simulation and field data.

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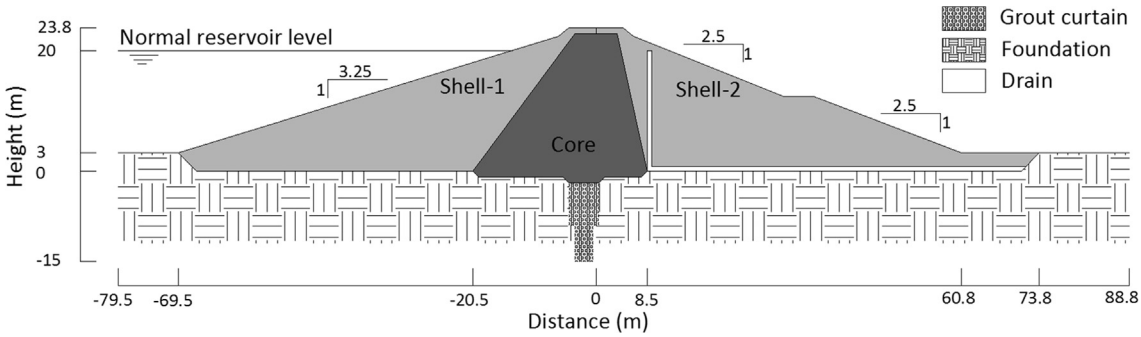

Fig. 1. Main cross section of the studied dam.

This paper aims to present a probabilistic stability analysis of a zoned earth-filled embankment dam located in France. Three soil properties (C', ϕ' and γ_d) of two different zones, thus 6 random variables are considered in the analysis. The failure probability and safety factor distribution of the dam under steady state flow condition for two exploitation conditions (normal and seismic loading conditions) are provided. In addition, the effect of distribution type for input parameters on dam reliability is also investigated.

Compared to the previous works on the reliability analysis of embankment dam stability, the following specific features are developed in the present paper:

- Three soil properties (C', ϕ' and γ_d) are described as random variables which follow underlying distributions, to consider the soil variability. The distribution type and relating parameters are determined using in-situ measurements or laboratory test results. These characteristics are generally estimated from hypothetical or statistical considerations, as done in [4–9]. The methods used for data processing on the filed data in this study are based on [3].
- The present work introduces a reliability method, Sparse Polynomial Chaos Expansion (SPCE) [10–12], to embankment dams. It is an extension of the Polynomial Chaos Expansions (PCE) [10,11], which is a powerful vehicle for metamodeling. The method has well-established mathematical concepts (expansion of the system response on a suitable basis) and needs no assumption of the performance function unlike the RSM which requires an "a priori" form. The main idea of the PCE is to replace the time consumed deterministic model by a meta-model, and then perform a Monte Carlo simulation with respect to the meta-model. It can provide interesting results (distribution, statistical moments of the system response and failure probability), thus more insights into the dam reliability than the conventional methods, such as FORM, FOSM, and quasi-MC methods which were used in the previous works of [3,4,7,8]. For the SPCE, the non-significant polynomials are discarded from PCE using a step-wised regression technique, in order to decrease the number of deterministic model calls when constructing a meta-model. Application of the SPCE to other geotechnical engineerings, such as bearing capacity of strip footings and tunnel face stability, can be found in [13,14]. It was shown that the SPCE presents high efficiency in reliability analysis compared to the RSM and quasi-MC methods, especially for the cases of low failure probability and for high dimensional stochastic problems [13,14].
- Two deterministic models are developed in the study and are implemented to the SPCE reliability analysis. The first one is a numerical model based on the strength reduction method (SRM), and the second one is an analytical model based on the limit equilibrium theory (LEM). Using the analytical model in a reliability analysis can reduce the computational time, while the development of a numerical model permits to compare the obtained reliability results with those of the analytical model. In the works of [4–9], only one deterministic model was used, and thus there was no comparison between the two methods (SRM and LEM) in probabilistic frameworks.

The main contribution of this paper is to present a reliability analysis of a real dam by using a powerful meta-modelling technique SPCE and by exploiting the available measurement data. The article is started by a brief presentation of the studied dam and the relating geotechnical data. Then, the statistical parameters of the soil properties (C', ϕ' and γ_d) are determined. The reliability analysis results of the dam are given after a description of the SPCE and the development of the two deterministic models. Some complementary works are carried out to provide more interesting insights into the dam reliability: comparison of the two deterministic models in a probabilistic framework, effect of the distribution type for the input variables on the reliability, and the contribution of each input variable to the variability of the dam FoS.

2. Variability modelling of the dam soil properties

The present study is based on a well-documented embankment dam located in France. This section focuses firstly on presenting the studied dam and the available measurements. Then, statistical parameters of the three soil properties (C', ϕ' and γ_d) are determined using in-situ measurements or laboratory tests in order to simulate them by means of random variables.

2.1. General geotechnical description of the dam

Fig. 1 presents the main cross section of the studied dam. It is a 170 m long and 23.8 m high earth-filled dam completed in the year 1998. It closes a valley covered with alluvial deposits and can retain a reservoir of about 5 h m^3. The normal and maximal reservoir water level is respectively 20 and 21.6 m.

As presented in Fig. 1, the dam is formed by three different zones including a core constituted with sandy silts and two backfill zones constituted with gravelly sands in respectively the upstream and downstream part of the core. These three zones are respectively named as Core, Shell-1, and Shell-2. A vertical and an horizontal drain were installed in the downstream part in order to collect the water flows and to lower the phreatic surface inside the dam. In the foundation, a waterproof grout curtain was realized with a depth of around 15 m.

The materials constituting the dam were collected from the vicinity of the dam site. Two different types of soils can be identified in the valley. The first type is gravelly sands resulting from the alteration of shales on slopes and uplands which dominate the valley. The foundation of the dam is considered as gravelly sands according to the site investigation. This material is used for the construction of the Shell zone. The second soil type, the sandy silts, can be found on the bottom of the valley and on the slopes. It was used for the construction of the Core zone. Fig. 2 presents the maximum, the average and the minimum granulometry for these two soil types. The curves in Fig. 2 are based on 37 particle size analyses for the gravelly sands and 27 analyses for the

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