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Integrated certainty and uncertainty evaluation approach for seepage control effectiveness of a gravity dam

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ABSTRACT

The seepage problems of dam engineering with complex seepage control measures are usually investigated by numerical simulation methods such as the finite element method (FEM). In general, the material and geometrical parameters and the boundary conditions on dam seepage are regarded as definite values. The heterogeneous and uncertain changes of seepage parameters and boundary conditions, which are caused by seepage control measures and material aging, are not considered. To describe more comprehensively the seepage behavior of a gravity dam and to identify more objectively the seepage control effectiveness of a gravity dam, the conventional FEM implementing numerical analysis for dam seepage is combined with the nonprobabilistic convex set–based method. Firstly, the FEM is introduced to implement the detailed simulation of typical seepage control measures and the certain seepage field analysis. Then a nonprobabilistic convex set–based numerical simulation method, which is suitable for the description of the uncertain seepage field of a gravity dam, is presented. The influence range of seepage control measures can be determined with the proposed method without the probability distribution knowledge of uncertain parameters. Lastly, an actual gravity dam undergoing seepage reinforcement is taken as an example. The seepage control effectiveness of the gravity dam is assessed with the FEM-based calculation model of the seepage field and the analysis model of the uncertain seepage field before and after seepage control implementation. In addition, the effect of the seepage field on the stress field is considered to fulfill the further analysis for the process and mechanism of seepage control of typical measures.

1. Introduction

In the course of service, a gravity dam suffers from a variety of adverse effects of load and material aging, which can lead to serious cracks in the dam body and fracture coalescence in the dam foundation. In this way, seepage risk emerges. On the one hand, the seepage flow will erode the dam body and bedrock (especially the soft structures), which will decrease the durability. On the other hand, it will change the stress condition of the dam, adversely affecting the strength and stability of

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the dam, and even leading to the catastrophic consequence of dam instability [1–5]. Therefore, in dam engineering, the prevention and control of dam seepage has always had great importance, and a series of seepage control measures combining seepage prevention (such as impervious curtains) and seepage diversion (such as drainage holes) have been proposed.

Traditional numerical simulation of the seepage field of gravity dams and the evaluation of the seepage control effectiveness were performed by numerical methods such as the finite element method (FEM), where the seepage coefficient, geometrical parameters, and boundary conditions of the dam body and foundation had fixed values [6–10]. However, in practice, these parameters will change constantly during the long-term service of the dam body-foundation system, and the heterogeneity and uncertainty will become more and more prominent because of the seepage control measures [11–15]. Research in dam engineering and other areas has shown that the uncertainty will have a significant impact on the results, and sometimes even lead to misjudge. Therefore, as for the stochastic FEM that is often used to solve or deal with uncertain problems of parameters and boundaries, it is usually hard to meet the demand of the probability distribution or statistical properties of uncertain parameters in practice [16,17].

In this article, the nonprobabilistic convex set theory and analysis method with a low requirement of uncertain information are introduced to characterize the uncertainties of the physical parameters related to seepage calculation, the initial conditions of the seepage field, and boundary conditions [18–22]. By combining the nonprobabilistic convex set theory with the FEM-based deterministic analysis method to obtain the certain and uncertain seepage fields of the gravity dam, we propose a response calculation model and analysis method for the gravity dam seepage field based on bounded uncertain parameters, with the hope of presenting the seepage properties of the gravity dam after seepage control measures more comprehensively, and evaluating the effectiveness of seepage control measures more scientifically.

The rest of the article is organized as follows. Firstly, the detailed simulation technology of the drainage holes is introduced to evaluate the effectiveness of seepage control measures of a gravity dam with use of the FEM. Secondly, the nonprobabilistic convex set theory and method are introduced to study the uncertainty evaluation method and model of seepage control measure effectiveness based on the uncertain characteristics of seepage parameters, initial conditions, and boundary conditions of gravity dams. Lastly, the methods and models are applied to evaluate the seepage control effectiveness of a gravity dam project that has experienced several seepage control measures by our setting up an FEM model of the dam seepage field and an uncertain seepage field analysis model before and after seepage control measures as well as our considering the influence of seepage field changes on the stress field.

2. FEM simulating seepage control measures and evaluating their effectiveness for a gravity dam

From an engineering perspective, the layout of drainage holes (often laid into one or more roads, one or more layers of drainage curtain according to certain rules) and dredging of installed drainage holes are the commonest seepage control measures that can significantly affect the water head distribution of the seepage field in a dam body-foundation system and play a positive role in drainage and depressurization. However, how to identify the effect of drainage holes is a difficult problem when the FEM is applied to seepage field analysis. For the finite element meshes of a seepage field, the element size is usually 5–10 m, while the pore size of the drainage hole is usually only 5–10 cm, and the hole distance is also small (about 3–5 m), but depth is often up to tens of meters. The local grid refinement of drainage holes to simulate the drainage hole seepage property is often adopted in conventional methods, in which the number of units must be increased dramatically, seriously affecting the calculation efficiency and accuracy. In terms of the problem, a variety of scholars have been exploring solutions for the purpose of providing a reasonable simulation for the effect of drainage holes [6–9]. The improved drainage substructure method based on the nodal virtual flux method and drainage substructure technology solves the problem of the seepage field when the drainage hole passes through or does not pass through the free surface from the aspects of theory and algorithms. In this regard, the actual vicinity of the drainage seepage field can be reflected more precisely and accurately, resulting in wide application of this method in practical engineering seepage analysis with complex seepage control structures [23,24]. Therefore, the improved drainage substructure method is introduced in this article to realize the detailed simulation of drainage holes and the evaluation for seepage properties of gravity dams.

2.1. Seepage problem with free surfaces

In general, in terms of unsteady seepage, the water head varies with time. Therefore, according to the generalized Darcy law, the follows holds:

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z\frac{\partial h}{\partial z}\right)=S_s\frac{\partial h}{\partial t}, \tag{1}$$

where h denotes the water head, k_x, k_y, and k_z represent the permeability coefficients in the directions of x, y, and z, respectively, S_s is the unit storage (m^{-1}).

The governing equation, Eq. (1), is subjected to the initial condition, $h(x, y, z, t)|_{t=0} = h(x, y, z, 0)$, and the following boundary conditions: