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# Seepage safety monitoring model for an earth rock dam under influence of high-impact typhoons based on particle swarm optimization algorithm

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**Abstract**

Extreme hydrological events induced by typhoons in reservoir areas have presented severe challenges to the safe operation of hydraulic structures. Based on analysis of the seepage characteristics of an earth rock dam, a novel seepage safety monitoring model was constructed in this study. The nonlinear influence processes of the antecedent reservoir water level and rainfall were assumed to follow normal distributions. The particle swarm optimization (PSO) algorithm was used to optimize the model parameters so as to raise the fitting accuracy. In addition, a mutation factor was introduced to simulate the sudden increase in the piezometric level induced by short-duration heavy rainfall and the possible historical extreme reservoir water level during a typhoon. In order to verify the efficacy of this model, the earth rock dam of the Siminghu Reservoir was used as an example. The piezometric level at the SW1-2 measuring point during Typhoon Fitow in 2013 was fitted with the present model, and a corresponding theoretical expression was established. Comparison of fitting results of the piezometric level obtained from the present statistical model and traditional statistical model with monitored values during the typhoon shows that the present model has a higher fitting accuracy and can simulate the uprush feature of the seepage pressure during the typhoon perfectly.


*Keywords:* Monitoring model; Particle swarm optimization algorithm; Earth rock dam; Lagging effect; Typhoon; Seepage pressure; Mutation factor; Piezometric level

## 1. Introduction

China is located in the western Pacific Ocean region, which is significantly influenced by typhoons. On average, eight to nine typhoons or gales make landfall in China each year (Xiao et al., 2011). Typhoons and storms after landfall cause heavy rainfall, floods, and other catastrophes, which seriously threaten lives and property (Tang et al., 2011). The factors of hazards, especially the impacts of heavy rainfall and storm surges during a typhoon, appear as sudden impact loads (Feng and Luo, 2009). For an earth rock dam and its foundation, the sharp rise of the reservoir water level caused by heavy rainfall during a typhoon is equivalent to a sudden loading and unloading process (Lin and Jeng, 2000). The location of the phreatic line in an earth rock dam directly impacts its side slope stability. Therefore, it must be measured during the safety monitoring of the earth rock dam (Chigira et al., 2013).

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Li et al. (2003) established an element-free method (EFM) with a free surface based on the moving least square method, which requires only the information at element nodes, and successfully analyzed the steady seepage and transient seepage in a uniform earth dam. Chen et al. (2010) simulated the fracture or drainage segment in a rock mass using a special sub-element with definite seepage characteristics and deduced the governing equation for the composite element using the variational principle. Kazemzadeh-Parsi and Daneshmand (2012) proposed a new non-boundary-fitted finite element method, the smoothed fixed grid finite element method (SFGFEM), to solve the unconfined seepage problem in domains with arbitrary geometry and continuously varied permeability. Through transformation of the area integral into the line integral around edges of smoothing cells, the gradient smoothing technique was used to obtain the element matrix, and the phreatic surface was computed through the iterative process under nonlinear boundary conditions. Jiang et al. (2010) established a three-dimensional numerical manifold method for unconfined seepage analysis using a tetrahedral mathematical mesh. The element conductivity matrix and global simultaneous equations for unconfined seepage analysis were derived by constructing hydraulic potential functions of the manifold element. Hashemi and Hatam (2011) conducted numerical simulation of two-dimensional transient seepage using the radial basis function-based differential quadrature (RBF-DQ) method. Compared with the analytical finite element method and existing numerical solutions from the literature, the RBF-DQ method was able to produce more accurate results for seepage analysis. Cho (2012) assumed that the hydraulic conductivity was different for different layers of an embankment, and that the hydraulic conductivity in a layer was uncorrelated with that in other layers. Two-dimensional random fields were generated using the Karhunen-Loève expansion in a manner consistent with a specified marginal distribution function and an autocorrelation function. A series of seepage analyses of embankment foundation systems was performed using random fields generated to study the effects of uncertainty due to the spatial heterogeneity of the hydraulic conductivity on the seepage flow. Ahmed (2009) considered the hydraulic conductivity of earth dams a spatially random field following a lognormal distribution and conducted corresponding unconfined seepage analysis. Results showed that the seepage discharge obtained from the stochastic solution was lower than that obtained from the analytical solution, and the free surface was observed to emerge at a point lower than the location obtained from the analytical solution. Most of the dam seepage analyses described in the literature were conducted under normal operating conditions. However, in recent years frequent extreme weather conditions have presented severe challenges to the safe operation of dams worldwide (Hossain et al., 2010; Lubchenco and Karl, 2012; Xiang et al., 2012). Development of an accurate seepage safety monitoring model for an earth rock dam during a high-impact typhoon will significantly benefit real-time security control of earth rock dam seepage behaviors (Gu and Wu, 2006).

In this study, seepage safety analysis of an earth rock dam under the influence of a high-impact typhoon was conducted, and the seepage pressure in the dam body during the typhoon was quantified by establishing a statistical theoretical model based on the particle swarm optimization (PSO) algorithm. The traditional statistical model of the piezometric level in earth rock dams can be divided into four parts: the upstream water level component, the rainfall component, the temperature component, and the time effect component. The piezometric level was assumed to be linearly correlated with the upstream water level and rainfall (Fu et al., 2011). However, an analysis based on monitoring data indicated that when a reservoir encountered heavy rainfall and the potential historical extreme reservoir water level under the influence of a typhoon, the correlation between the piezometric level and environmental variables exhibited obvious nonlinearities, and the piezometric level increased sharply during the typhoon. It was found that using the traditional statistical model to fit the piezometric level would produce an underfitting problem (Hashemi and Hatam, 2011). The cause of this phenomenon can be explained from two aspects: when a reservoir reaches a new higher water level after impoundment, the material of the earth rock dam body exhibits collapsibility and rheidity because of water immersion, producing new seepage channels and leading to an increase in the piezometric level; some originally inactive seepage channels at the bottom of the reservoir begin to leak, further increasing the piezometric level. For these reasons, a mutation factor was introduced in this study to simulate the nonlinear variation of the piezometric level under the influence of the typhoon. To verify the model, the earth rock dam of the Siminghu Reservoir in Zhejiang Province was used as a case study. The present model was used to fit the piezometric level in the dam during Typhoon Fitow in 2013. The effectiveness of the present model was verified by comparing its results with those of the traditional statistical model.

## 2. Basic theories

### 2.1. Construction of piezometric level statistical model

An analysis of measured data shows that the seepage pressure in an earth rock dam body is primarily influenced by factors such as the upstream water level, rainfall, the ambient temperature, and the time-varying characteristics of the dam materials (Wu, 2006). In addition, in order to simulate the uprush feature of the seepage pressure under the influence of a typhoon, a mutation factor is introduced into the model. The novel statistical model of the piezometric level in an earth rock dam is thus as follows:

$$P = P_{\mathrm{H}} + P_{\mathrm{R}} + P_{\mathrm{T}} + P_{\theta} + P_{\mathrm{E}} \tag{1}$$

where $P$ is the dam body piezometric level, $P_{\mathrm{H}}$ is the upstream water level component, $P_{\mathrm{R}}$ is the rainfall component, $P_{\mathrm{T}}$ is the temperature component, $P_{\theta}$ is the time effect component, and $P_{\mathrm{E}}$ is the mutation factor caused by the typhoon.