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Research Paper

Integration of creep into a modified hardening soil model for time-dependent analysis of a high rockfill dam

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ABSTRACT

This paper proposes an approach to extend a modified hardening soil model into the time-dependent analysis of high rockfill dams. The key feature of the extended model is the integration of a creep model and the double yield surface elasto-plastic model, via modifying the hardening functions. The integrated model is validated by a laboratory multistage creep test. Results from three-dimensional analyses including the without creep and with creep considerations of the Nam Ngum 2 dam have been compared with the in-situ measurements. The prediction of dam deformation can be significantly enhanced by the proposed model.

1. Introduction

Rockfill structures are a crucial element of rockfill dams, which have been broadly constructed in many parts of the world due to their advantages of good adaptability to topography, available local materials and low construction investment. Movement of rockfill materials can lead to dam failure, particularly concrete-faced rockfill dams (CFRDs) that have upstream concrete slabs as an impermeable element. Breaching of the slab, as a result of excessive rockfill movement during the construction and impoundment, is the main concern of a CFRD design. In the design and safety assessment procedure, the finite element method (FEM) has been broadly used as a tool for the stress and deformation analysis of several rockfill dams modeled under various essential situations. A crucial element of this approach is a constitutive model, known as the Soil model, representing the stress-strain behavior of rockfill materials. Selection of the constitutive model depends on the particular assumptions of the analysis, which can be divided into two major categories, namely, time-dependent and time-independent analyses. It is widely known that rockfills are time-dependent materials of increasing interest to many researchers. The time-dependent analysis of rockfill dams has mostly received attention regarding long-term deformation affecting rockfill dam safety during the operational stage [1–3] and has been omitted for the stage of construction and first impounding. The processes of the construction and impoundment stages for high CFRDs, nevertheless, are time consuming, taking approximately 3–6 years. The rockfill creep of a high CFRD mostly occurs during the construction process and clearly influences the stresses and deformations of the concrete face as well [4,5]. Moreover, dam deformation analyses without consideration of time dependence in the past [6–9] have commonly provided underestimated values of the predicted settlement. Therefore, it is more reasonable to consider the rockfill creep in the dam simulation during the construction and first impoundment stages [10].

In the case of a high rockfill dam, the complexity of construction sequences, a long construction period and a long impoundment period make it necessary to consider many loading increments in the analysis together with the creep between them. The strategy currently used is to perform a time-independent analysis for each incremental loading step and a time-dependent analysis for each constant stress state, alternately. The essential elements are thus (1) reasonable and rational constitutive models for both time-independent and time-dependent behaviors and (2) the integration of the above two models.

In any layers within the high dam, the rockfill materials in the dam body are subjected to a broad stress range and high confining pressures (at the center of the bottom level) under given loading times during the construction process. Large-scale triaxial creep tests have been performed by researchers to study the factors influencing the creep behaviors and to develop creep models for

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the time-dependent analysis of rockfill materials [11–15]. These studies were principally focused on the effect of varied confining pressures upon the creep characteristic of rockfill materials. Some of these studies have developed a creep model for use with finite element analysis programs. Even though the simulated results have shown good agreement with laboratory test results, the predicted dam deformations were not satisfactorily matched by in situ measurements. Moreover, with long testing periods, triaxial creep tests require advanced systems and facilities. The one dimensional (1D) creep test is therefore an alternative engineering practice for dam design.

Presently, numerous constitutive models, as well as new approaches to modeling time-dependent behaviors of rockfills, have been proposed to predict creep deformation of rockfill dams such as Wen et al. [16] and Kong et al. [17]. According to Liingaard et al. [18], these models can be widely categorized into two main groups, i.e., a rheological group and an empirical group. The rheological models are a combination of simple mechanical models, such as elastic springs, plastic sliders, and viscous dashpots. These viscoelastic and viscoplastic models have been developed and adopted to analyze the behaviors of some rockfill dams [1,4,19,20]. For the empirical model, the mathematical functions are appropriately selected to fit with experimental results, e.g., the creep, stress relaxation, and constant rate from strain tests. Several researchers have employed empirical models to analyze the time-dependent deformations of high rockfill dams. For instance, a creep model under high confining pressure expressed by the power function was used to simulate the two-dimensional plain-strain condition of the Shuibuya CFRD [3]. In addition, the empirical creep model based on an exponential function was employed to model the rockfill materials of the Tianshengqiao-I CFRD [21]. Nevertheless, the parameters used to predict the long-term deformation of these dams were obtained on the basis of back-analysis methods. Apart from creep, the time-independent deformation calculated by the Duncan-Chang's hyperbolic elastic model cannot reflect some of the essential features of the rockfill [e.g., 10,22].

So far, few researchers have modeled high CFRDs during the stage of construction with a time-dependent constitutive model. Gan et al. [4] introduced a viscous–elastic–plastic model, employing the Duncan-Chang model for transient elastic strain, to simulate the creep deformation of the rockfill of the Jiudianxia CFRD. However, as a result of the one-dimensional condition of the creep test, the effect of confining pressure was not taken into account on the determination of the viscosity coefficient parameters of their proposed model. The dilatancy was also not considered. Several empirical creep models considered together with an elasto-plastic model have been introduced by some researchers. Zhou et al. [5] proposed a new creep model, based on a power function, to combine with an elasto-plastic model for the creep analysis of the Shuibuya CFRD from the construction stage to the operational stage. However, an interaction effect between the elasto-plastic model and the creep model was not clear as to how the creep strains affected the elasto-plastic behavior for the next loading step.

To reasonably analyze the deformation of high rockfill dams under complex construction sequences, long construction periods and impounding using numerical methods, reasonable constitutive models for both time-independence and time-dependence in conjunction with the appropriate integration of them are necessary. Therefore, this paper proposes an approach to extend an elasto-plastic constitutive model into the time-dependent analysis of high CFRDs. The key feature of the extended model is the integration of a creep model, relying on the variation of confining pressures and stress ratios, and the double yield surface elasto-plastic model, known as the modified Hardening Soil (modified HS) model [9]. The hardening functions are modified in order to link an interaction between the creep model and modified HS model. Then, the integrated model, known as the Hardening Soil Creep (HSC) model, is applied to the FEM computer program ABAQUS via the defining subroutine UMAT. As mentioned previously, it is more convenient to perform a creep test of rockfill materials under 1D condition. This study also presents the procedure for obtaining the parameters of the creep model, formulated from triaxial creep, from 1D creep tests. The developed HSC model is validated by comparing the results between the simulation and the laboratory multistage creep test. Three-dimensional (3D) analyses of the Nam Ngum 2 (NN2) CFRD from the construction stages until after the full filling of water are conducted with and without the consideration of creep. Comparisons between the predicted results and the field monitoring data of the NN2 CFRD are made to evaluate the performance of the HSC model.

2. Rockfill creep model

The developed creep model was derived from triaxial creep testing results with different stress states of rockfill materials in a previous study [13,23]. The details of development can be found in Pramthawee et al. [24]. It was based on a basic power function, which is more suitable than other functions [14], because the numerical implementation is simple. As indicated in a previous study, confining pressure plays an important role in the mechanical properties of rockfills [25]. Likewise, the variation of stress affects the creep properties as well [12]. The confining pressure, stress ratio, and deviator stress are the principal factors taken into account for the developed creep model in this study.

2.1. Composition of the creep model

The developed creep model is concisely explained in term of axial creep strain $\varepsilon_a^c(t)$ and volumetric creep strain $\varepsilon_v^c(t)$ as follows:

$$\varepsilon_a^c(t) = A_a(t)^{n_a} \tag{1}$$

$$\varepsilon_v^c(t) = A_v(t)^{n_v} \tag{2}$$

$$\frac{A_a}{\sigma_3/p_a} = \alpha_a(\sigma_1/\sigma_3)^{\beta_a} \tag{3}$$

$$\frac{A_v}{\sigma_3/p_a} = \alpha_v(\sigma_1/\sigma_3)^{\beta_v} \tag{4}$$

$$n_a = \eta_a\left(\frac{\sigma_1-\sigma_3}{p_a}\right)^{m_a} \tag{5}$$

$$n_v = \eta_v\left(\frac{\sigma_1-\sigma_3}{p_a}\right)^{m_v} \tag{6}$$

σ_1 and σ_3 are the major and minor principal stresses, respectively. The atmospheric pressure p_a is equal to 101.325 kPa. As in Eqs. (1) and (2), the initial creep parameter $A_a \,\&\, A_v$ and the creep rate parameter ($n_a \,\&\, n_v$) can be determined from the best fitting curve for the power function of the relationship between axial/volume creep strain and elapsed time, which is obtained from experimental results at a constant confining pressure. a and v denote the axial and volume components of strain, respectively. Then, A_a, A_v and n_a, n_v are further used to determine the constant creep parameters $\alpha_a, \beta_a, \eta_a, m_a, \alpha_v, \beta_v, \eta_v$ and m_v. Fig. 1 demonstrates an example of the regression analysis approach for determining these parameters. The coefficient creep parameters $\alpha_a, \beta_a, \alpha_v$ and β_v can be determined from the correlations of the normalized parameter A with σ_3/p_a and σ_1/σ_3 as described in Eqs. (3) and (4), respectively. Based on