Simulation of creep deformation of faced rockfill dam based on secondary development of ABAQUS

Hui Chen*, Yanyi Zhang
State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, Key Laboratory of Construction and Safety of Hydraulic Engineering of Ministry of Water Resources, China Institute of Water Resources and Hydropower Research, 20 West Chegongzhuang Rd., Haidian District, Beijing 100048, China
*Corresponding author: chenhui@iwhr.com

Abstract. The creep deformation of concrete face rockfill dam is one of the key factors affecting the safety and performance of a concrete faced rockfill dam. In this paper, creep deformation process was carried out by secondary development based on ABAQUS software. A concrete faced rockfill dam in Laos is the research object of long-term deformation inversion. The calculated results are in good agreement with the measured analysis results. The proposed method can provide reference for the long-term deformation of earth-rockfill dam.

1. Introduction
Concrete faced rockfill dam (CFRD) develops rapidly[1-2]. Since the stiffness of concrete face is much higher than that of rockfill body, there is a natural difficulty in deformation coordination between the two. Therefore, the deformation control of concrete faced rockfill dam has attracted much attention [3]. The deformation of dam body, especially the long-term deformation, has a great influence on the stress deformation and crack prevention of face slab. The creep deformation of rockfill is one of the main components of the long-term deformation. One dimensional empirical model is often used abroad. In China, Shen Zhujiang earlier studied the creep model of rockfill [4] and proposed a three-parameter exponential model [5]. Subsequently, Li Guoying et al. [6], Deng Gang et al. [7], and Wang Xiaogang [8] successively proposed a variety of three-dimensional calculation models for long-term deformation of rockfill materials. The calculation and analysis of concrete faced rockfill dam with creep model can better reflect the settlement deformation law of the dam body after completion and better predict the stress and deformation of the face slab. At present, the finite element calculations of earth and rockfill dam are mostly based on the self-designed complex finite element program, and there are few studies based on commercial software.

In this paper the relevant programs of the creep deformation model of rockfill by using the interface of secondary development platform provided by ABAQUS, are written and applied to the calculation of actual cases.

2. Related model development and calculation methods of ABAQUS

2.1. Incremental method
The calculation of ABAQUS adopts incremental method. In this paper, the deformation caused by stress application is divided into instantaneous stress deformation and lagged long-term deformation, and
incremental stress deformation refers to the instantaneous stress deformation after stress application. For each element, the element modulus matrix of instantaneous stress and deformation can be calculated according to the current stress condition, and the stiffness matrix of this incremental step can be obtained after summing up the calculation domains. Calculate the deformation increment according to the load vector increment, and then solve the strain increment of each element. According to the strain increment $\Delta \varepsilon$, the corresponding stress increment $\Delta \sigma$ is derived. The Jacobian $\frac{\partial \Delta \sigma}{\partial \Delta \varepsilon}$ is given. Then update the state variables associated with the solution result.

The total amount of deformation and strain at the end of each incremental step can be obtained by accumulating the deformation increment and strain increment obtained by each incremental step.

2.2 Secondary development of instantaneous stress and deformation model
In this paper, the instantaneous stress and deformation relationship of each element adopts Duncan's nonlinear model [9]. The secondary development in ABAQUS has been introduced in many literatures [10], which will not be repeated.

2.3 Secondary development of creep deformation models
The hysteretic long-term deformation after the stress applied is essentially coupled with the instantaneous deformation, and there is no distinct distinction between them. However, following the practice of the empirical models of long-term deformation, the instantaneous strain increment $\{\Delta \varepsilon_{\text{instant}}\}$ corresponding to the stress increment $\{\Delta \sigma\}$ is also calculated in this paper. In addition, through the secondary development of long-term deformation model in ABAQUS, the long-term deformation increment $\{\Delta u_{\text{creep}}\}$ corresponding to the time step $\Delta t$ of each load increment $\{\Delta P\}$ is directly calculated, and then the long-term strain increment is obtained.

The steps to calculate creep deformation using time increment are as follows:

1. The process of filling, impoundment and operation of the dam is divided into several analysis steps. The corresponding analysis step first calculates the instantaneous deformation and obtains the element stress and stress level.

2. Each analysis step is divided into several smaller periods $\Delta t$, and it is assumed that the stress in this period remains unchanged.

3. The final volume creep $\varepsilon_{vt}$ and shear creep $\gamma_t$ in this period of $\Delta t$ time are calculated, and then the volume creep rate $\dot{\varepsilon}_v$ and shear deformation rate $\dot{\gamma}$ are calculated. Then the creep increment and accumulated flow variables in this period of time are calculated, so as to obtain the creep strain increment in this period.

4. According to the calculated displacement and stress increment, and the displacement and stress obtained in the previous period of superposition, the cumulative displacement and stress can be obtained.

The interface program involved in the secondary development of long-term deformation of rockfill is mainly material custom program UMAT. The main working principle of UMAT subroutine is as follows: Obtain the corresponding stress increment according to the incoming strain increment in ABAQUS. The Jacobian matrix is deduced, that is, the rate of change of stress increment to strain increment; Update and evaluate related state variables, including variables passed in by the interface and variables to be updated.

3. Creep model of rockfill material
The three-parameter index model [5] suggested by Shen Zhujiang is adopted to calculate the long-term deformation of rockfill. Its curve is in the form of:

$$\varepsilon_{\text{creep}} = \varepsilon_i + \varepsilon_t \left(1 - e^{-at}\right)$$  (1)
Where: $\varepsilon^{\text{creep}}$ is creep; $\varepsilon_i$ is the initial creep; $\varepsilon_f$ is the final flow creep; $\alpha$ is the initial relative deformation rate.

The creep rate can be obtained by derivative of the above equation:

$$\dot{\varepsilon}^{\text{creep}} = \alpha \varepsilon_i e^{\alpha t}$$

(2)

The creep rate can be obtained by derivative of the above equation:

$$\dot{\varepsilon}^{\text{creep}} = \alpha \varepsilon_i e^{\alpha t}$$

(3)

The creep rate is decomposed into volume creep rate and shear deformation rate, and the calculation formula is as follows:

$$\varepsilon_{v}^{\text{creep}} = \alpha \varepsilon_i \left(1 - \frac{\varepsilon_f}{\varepsilon_i}\right)$$

(4)

$$\gamma_{f}^{\text{creep}} = \alpha \gamma_i \left(1 - \frac{\gamma_f}{\gamma_i}\right)$$

(5)

Where: $\varepsilon_{v_i}$ is the final volumetric creep variable; $\gamma_{f_i}$ is the final shear creep variable; $\gamma_i$ and $\gamma_t$ represent the accumulated volumetric creep and shear creep at time $t$.

$$\varepsilon_{v_i} = b \left(\frac{\sigma_i}{p_a}\right)$$

(6)

Where: $\sigma_i$ is the confining pressure; $p_a$ is atmospheric pressure.

$$\gamma_t = d \left(\frac{s_l}{1 - s_l}\right)$$

(7)

Where: $s_l$ is the shear stress level.

Using the assumption of Prandtl-Reuss flow rule, the strain rate tensor can be expressed as:

$$\{\dot{\varepsilon}\}^{\text{creep}} = \frac{1}{3} \dot{\varepsilon}_{v}^{\text{creep}} \{I\} + \dot{\gamma}_{f}^{\text{creep}} \frac{\{s\}}{\sigma_s}$$

(8)

Where, $\{s\}$ is the deviatoric stress tensor; $\{I\}$ is the unit tensor; $\sigma_s$ is generalized shear stress.

This model has three parameters: $\alpha$, $b$ and $d$.

The long-term strain remains constant within the increment is assumed, then

$$\left\{\Delta \varepsilon^{\text{creep}}\right\} = \left\{\Delta \varepsilon_{v}^{\text{creep}}\right\} \Delta t.$$  

4. Creep model of rockfill material

4.1 Finite element model

A high concrete face rockfill dam in Laos is taken as a case study. The maximum dam height is 143.5m, the upstream slope is 1:1.4, the downstream slope is 1:1.6 above the elevation of 610 m, and the lower slope is 1:1.4. The partition of maximum cross-sectional material is shown in Fig. 1.

The three-dimensional finite element model of concrete face rockfill dam is shown in Fig. 2.

![Fig. 1. Schematic diagram of maximum cross-section](image-url)
4.2 Calculated parameters
The Duncan EB model parameters for instantaneous stress and deformation calculation of dam material and overburden are shown in Table 1.

The three-parameter creep model suggested by Shen Zhujiang is adopted. Through deformation inversion in the pre-settlement period, the consistent creep model parameters for each area of rockfill can reflect the actual situation well. The relevant parameters of $\alpha$, $b$ and $d$ are 0.0045, 0.002 and 0.0012.

Table 1. The parameters of Duncan's EB model obtained by inversion computation of stress strain condition during construction period

| Dam material zone | Shaded part of 3B1 | 3B2 | 3C1 |
|-------------------|--------------------|-----|-----|
| $R_f$             | 0.65               | 0.75| 0.75|
| $K$               | 850                | 1400| 1400|
| $n$               | 0.35               | 0.8 | 0.8 |
| $K_b$             | 350                | 1050| 1050|
| $m$               | 0.45               | 0.75| 0.75|
| $K_{ur}$          | 1700               | 2800| 2800|
| $\phi_{(\,)}$    | 53.5               | 56  | 56  |
| $\Delta\phi_{(\,)}$ | 8                 | 6   | 6   |

5. Inversion analysis results of long-term deformation of dam body
The dam has been pre-settled for 485 days from the end of filling to the pouring of face slab in the second stage. In the pre-settlement period, the load of the dam remains unchanged, and the deformation of the dam is mainly caused by the creep deformation of the rockfill.

The settlement increment calculation results at this stage are presented, as shown in Fig. 3. It can be seen that under the condition of constant load, the settlement distribution of the dam body is larger at the top and smaller at the bottom.
Fig. 3. Settlement increment calculation results of the dam during the pre-settlement period (unit : m)

The comparison between the measured and calculated settlement values of 11 monitoring points with different stake marks on the dam crest is shown in Fig. 4. The calculated values are consistent with the measured values well, and the settlements on both banks are small, while the settlements near the riverbed are large. The errors of the three measuring points near the right bank are slightly larger, which may be related to the difference in physical and mechanical properties and states of local rockfill materials.

Fig. 4. The comparison between the calculated values and the measured values of settlement at the dam crest

Fig. 5 shows the stress distribution of the first stage concrete face before pouring the second stage. The maximum major principal stress (maximum compressive stress) of the concrete face is about 2.6MPa, which occurs at the bottom of the concrete face. The minimum value of the small principal stress (the maximum tensile stress) is about 0.4MPa, which appears near the bank slope on the upper part of the concrete face. The stress state in the pre-settlement period is within the range of concrete strength.
Fig. 5. Principal stress distribution of the first stage concrete face before pouring the second stage (unit: MPa).

Fig. 6 shows the stress distribution of the left and right bank direction and slope direction of the first stage concrete face before pouring the second stage. The stress range of the left and right bank is -0.4MPa-1.8MPa. The stress range along the slope is -0.2MPa-2.4MPa. The stress of the upper concrete face near the bank slope is negative (tensile stress) in the left and right bank direction and along the bank slope direction. But the tensile stress is small.

Fig. 6. Stress distribution of different directions of the first stage concrete face before pouring the second stage (unit: MPa).
6. Conclusion
Based on the finite element software ABAQUS, the creep model subroutine of concrete faced rockfill dam is programmed. Thus, the numerical simulation of the long-term deformation of concrete face rockfill dam is realized.

The method is applied to a project, and the settlement results obtained by the inversion analysis are in good agreement with the measured results, which indicates that it is reliable to use ABAQUS to analyze the structural state of the concrete faced rockfill dam during the construction period and operation period after the secondary development.

This paper expands the application scope of ABAQUS software in earth-rockfill dam engineering, which can provide a reference for the calculation method of long-term deformation of face rockfill dam.

Acknowledgments
Financial support provided by the National Key R&D Program of China (no. 2018YFC0407103) is gratefully acknowledged.

References
[1] X.Q. Niu. Security of high concrete face rockfill dam consideration and conclusion Journal of Hydroelectric Engineering, 36(1): 104-111(2017).
[2] H.Q. Ma. 300 m grade concrete faced rockfill dam adaptability and countermeasures. Engineering Science, 13(12): 4-8, 19(2011).
[3] L.F. Wen, J.R. Chai, Z.G. Xu, et al. Deformation and stress behaviours of concrete-face rockfill dam built on sand and gravel foundation. Journal of Hydroelectric Engineering, 35(9): 63-77(2016).
[4] Z.J. Shen. A creep model of rock-fill material and determination of its parameters by back analysis. Scientific Research on Water Conservancy and Transportation, (4): 335-342(1994).
[5] Z.J. Shen, K.Z. Zhao. Back analysis of creep deformation of rockfill dams. Journal of Hydraulic Engineering, (6): 2-7(1998).
[6] G.Y. Li, K.Z. Zhao, Z.K. Mi. Influence of rheological behaviors of rockfills on stress-strain behaviors in concrete faced rockfill dam. Rock and Soil Mechanics, (S1): 117-120(2005).
[7] G. Deng, Z.P. Xu, S.X. Lu, et al. Analysis on long term stress and deformation of high concrete face rockfill dam in narrow valley. Journal of Hydraulic Engineering, (6): 639-646(2008).
[8] X.G. Wang Discussion on some problems observed in high earth-rockfill dams. Chinese Journal of Geotechnical Engineering, 40(2): 203-222(2018). (in Chinese)
[9] J. M. Duncan. Nonlinear analysis of stress and strain in soils. ASCE Journal of the Soil Mechanics and Foundation Division, 1970, 96(5): 1629-1653(1970).
[10] K. Fei, J.W. Zhang. Application of ABAQUS in geotechnical engineering. Beijing: China Water Conservancy and Hydropower Press(2009).