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Long-term deformation analysis of concrete faced rock-fill dam[1]

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Abstract. The crack of the concrete face slabs is an important influence factor of the safety of Concrete Faced Rock-fill Dam (CFRD) due to long-term deformation of the rock-fill. The long-term deformation characteristics of these CFRD under water load must be studied by taken the creep deformation and the wetting deformation of the rock-fill into account. In this paper, the seven-parameter creep is used to simulate the creep deformation of the CFRD, and the wetting deformation is simulated by the finite element method (FEM) using the double-line model as a user subroutine loaded into the ABAQUS code. In the calculation process, the stress variation yielded by the wetting deformation is calculated using the Duncan E-B model with the dry parameters, and subtracting the stress calculated with the wet parameters. A three-dimensional finite element analysis of long-term deformation on the Maerdang CFRD (in the Yellow River) is analyzed. The results show that the long-term deformation of the rock-fill has large influence on the stress and deformation of the CFRD. Therefore, the analysis of the stress and deformation of the CFRD cannot be ignored.

Key words. Concrete Face Rock-fill Dam (CFRD), creep deformation, wetting deformation, long-term deformation.

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1. Introduction

The height of the new Concrete Face Rock-fill Dams (CFRD) is gradually increased in China, the super-high CFRD (more than 250 m), the dam deformation control is the key technology for the construction of the super-high CFRD 1. The face slab is the crucial anti-seepage part of a CFRD, and it has a great influence on the safety of CFRD 2. Taking the dam deformation control into account, the wetting and creeping deformation are two key influencing factors of the deformation of face slab 3–7. Therefore, it is necessary to study the long-term deformation of the rock-fill. In recent years, the characteristics and the model for long-term deformation have been studied by many researchers. However, there are so many factors that affect the mechanism of a long-term deformation of a CFRD that there are few research results available to date.

Kim et al. [1] used numerical analysis and a large-scale triaxial test with monitoring data from other 29 CFRDs to obtain the deformation characteristics of a CFRD during the construction of the dam and the initial reservoir filling period. They established a generalized plasticity model and developed a three-dimensional finite element (TDFE) procedure, and the deformation of CFRD could then be evaluated. The creep properties of the cushion material of the CRFD by using the stress-type three axis test and an exponential decay function to fit the creep curve, and the three parameter creep model for rock-fill was put forward. This research provided the basis for the creep study of rock-fill and the creep analysis of an earth-rock dam. Based on the creep mechanism. Oldecop [2] found the main features of the delayed deformation of rockfill could be physically explained within the developed framework, and explored the fundamental phenomena that may be involved in the rockfill straining process, and developed a conceptual model able to explain the features of the observed behaviour. The result showed that creep deformation of the rock-fill was related to confining the pressure and the stress level. Under a high confining pressure and a high stress level, the creep stability obviously became slow. The creep deformation showed a good linear relationship to time, and the creep law of the rock-fill is similar under a different stress state using the double logarithmic coordinates. Based on the generalized suction theory, the generalized effective stress principle, the steady state void ratio and the principle of the steady state, Gan and Shen [3] assumed that the volume strain of water immersion was proportional to the index of confining pressure. The axial strain caused by wetting is calculated from the difference between the stress-strain curve of the saturated material and the stress-strain curve of the dry material, and the initial tangent modulus of the two curves is presumed to be the same, thus raising the wetting deformation model. Determined the relationship between the wetting strain and the stress state of the rock-fill though the wetting test with a single-line method and a double-line method in granite and metamorphic rocks and then put forward the wet model and model parameters of the rock-fill materials [4]. Based on the improved calculation model for wetting deformation. At present, most researchers focus on the influence of creep or wetting of the rock-fill material on the deformation of the dam [5]. In this paper, the influence of both creep and wetting of the rock-fill on the dam deformation is investigated. Therefore, there has important scientific and practical significance to analyze the long-term deformation of the rock-fill using the FEM, in determining the distribution variation law for the long-term deformation of the dam, and in analyzing the long-term deformation properties of rock-fill for the construction of CFRD.

2. Theoretical part

Rock-fill is the main part of a CFRD. The deformation is divided into instantaneous deformation and creep deformation. The creep deformation is very complex, and there are several aspects of the causes of rock-fill creep. The long-term deformation caused by the transmission and development of the partial dislocation or destruction of the rock-fill, and increased due to the wetting-drying cycles by rain or variation of the water levels. The research shows that the breaking and sliding of the gravel particles is the main reason of the creep deformation.

2.1. Seven-parameter creep model

The creep test results were analyzed, and the test results show that the stress state has great influence on the creep deformation of the rock-fill. In the three parameter model of rock-fill creep [6]–[8], the final volume creep $\varepsilon_{\mathrm{vf}}$ and the final shear creep γ_{f} are related only to the confining pressure σ_3 and stress level S_1. The creep mechanism and the creep test results both show that the final volume creep is related to the shear stress and has a nonlinear relationship between them. The increment of the creep variable will decreased with the increasing values of load.

The Merchant viscoelastic model is used to simulate the $\varepsilon - t$ attenuation curve under the constant stress condition [9]–[12], the formula of the creep relationship is as follows

$$\varepsilon = \varepsilon_{\mathrm{i}} + \varepsilon_{\mathrm{f}}(1 - \mathrm{e}^{-\alpha t})\,, \tag{1}$$

where ε is the creep, ε_{i} is the initial creep, ε_{f} is the final creep variable from the beginning of time t and α is the initial relative deformation rate. The creep rate can be expressed as

$$\dot{\varepsilon} = \alpha \varepsilon_{\mathrm{f}} \mathrm{e}^{-\alpha t}\,. \tag{2}$$

The creep rate is divided into the volume creep rate and the shear deformation rate, and the calculation formulas ares as follows:

$$\dot{\varepsilon}_{\mathrm{v}} = \alpha \varepsilon_{\mathrm{vf}} \left(1 - \frac{\varepsilon_{\mathrm{vt}}}{\varepsilon_{\mathrm{vf}}}\right)\,, \tag{3}$$

$$\dot{\gamma} = \alpha \gamma_{\mathrm{f}} \left(1 - \frac{\gamma_t}{\gamma_{\mathrm{f}}}\right)\,, \tag{4}$$

where $\varepsilon_{\mathrm{vf}}$ is the final volume creep variable and γ_{f} is the final shear creep variable. The parameters $\varepsilon_{\mathrm{vt}}$ and γ_{t} express that time has been accumulated in the volume creep variable, and the shear creep variable, and $\varepsilon_{\mathrm{vt}}$ is proportional to σ_3. According to the creep law of the test, the final volume creep of $\varepsilon_{\mathrm{vf}}$ and the final shear creep γ_f can be expressed using the simplest functional relationship

$$\varepsilon_{\mathrm{vf}} = b\left(\frac{\sigma_3}{P_{\mathrm{a}}}\right)^{m_1} + c\left(\frac{q}{P_{\mathrm{a}}}\right)^{m_2}, \tag{5}$$

$$\gamma_{\mathrm{f}} = d\left(\frac{S_l}{1-S_l}\right)^{m_3}, \tag{6}$$

where σ_3 is the small principal stress, P_{a} is the atmospheric pressure, b, c, d, m_1, m_2, m_3 and d are model parameters (b is equivalent to the final volume creep variables when σ_3 and P_{a} are equal, and d is the final shear creep variable (when the stress level S_l equals 0.5), and S_1 is the stress level. The calculation formula is

$$S_l = \frac{(\sigma_1-\sigma_3)}{(\sigma_1-\sigma_3)_f} = \frac{(\sigma_1-\sigma_3)(1-\sin\varphi)}{2(c\cos\varphi+\sigma_3\sin\varphi)}. \tag{7}$$

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

$$\dot{\varepsilon} = \frac{1}{3}\dot{\varepsilon}_{\mathrm{v}} + \dot{\gamma}\frac{\{s\}}{\sigma_s}, \tag{8}$$

where $\{s\}$ is the deviatoric stress tensor and σ_{s} is the generalized shear stress. The calculation formula is

$$\sigma_{\mathrm{s}} = \frac{1}{\sqrt{2}}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_1-\sigma_3)^2\right]^{1/2}. \tag{9}$$

The volume creep increment and the shear creep increment can be written as

$$\Delta\varepsilon_{\mathrm{vt}} = \dot{\varepsilon}_{\mathrm{v}}\Delta t, \tag{10}$$

$$\Delta\gamma_{\mathrm{t}} = \dot{\gamma}\Delta t. \tag{11}$$

If the time step length is Δt, the total volume creep variable and the shear creep variable of the tth moment are

$$\varepsilon_{\mathrm{vt}} = \sum \dot{\varepsilon}_{\mathrm{v}}\Delta t, \tag{12}$$

$$\gamma_{\mathrm{t}} = \sum \dot{\gamma}\Delta t. \tag{13}$$

2.2. *Subroutine for FEM and creep increment analysis of rock-fill*

The deformation of the rock-fill includes two parts: the instantaneous elastic-plastic deformation and the creep deformation changing with time. In this paper, the instantaneous deformation of the rock-fill is calculated using the Duncan-Chang

E-B model, and the creep deformation is calculated using the seven-parameter creep model. The initial stress method is used in the design of the subroutine for FEM of the creep. The creep deformation subroutine calculation process is shown in Fig. 1.

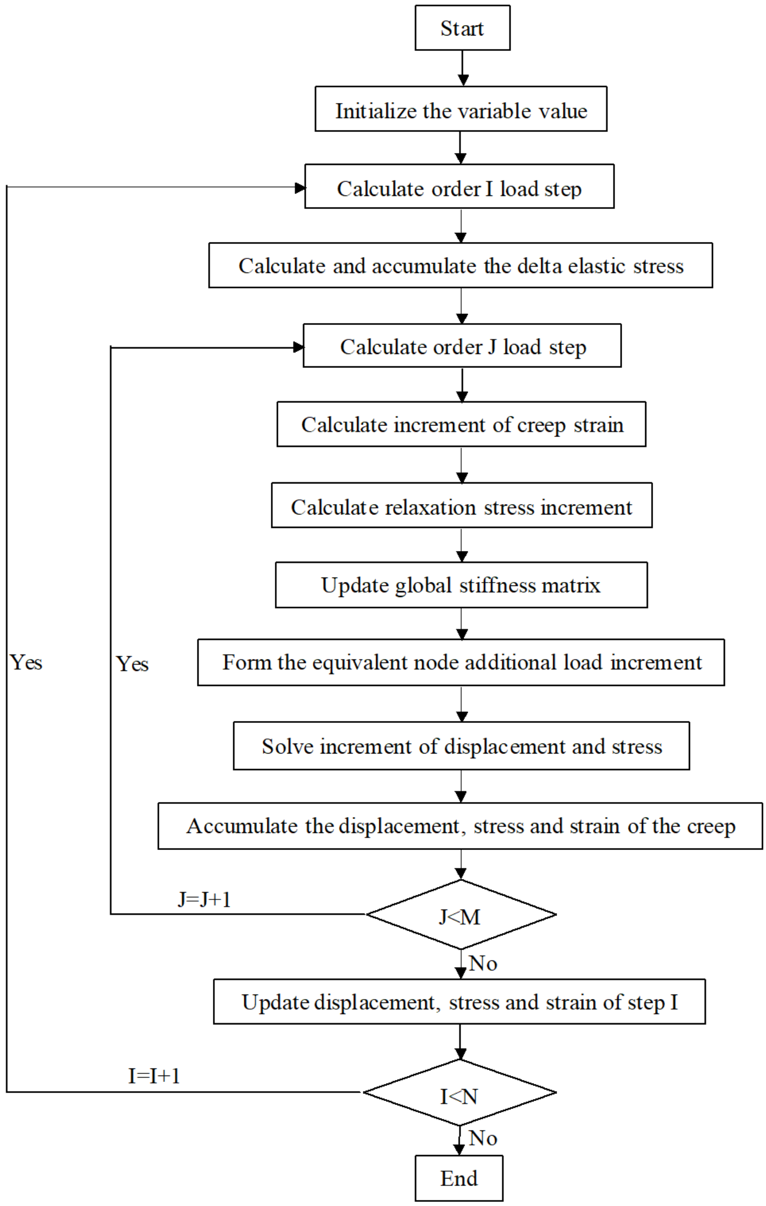

Fig. 1. Flow chart of creep deformation calculation using FEM

2.3. Wetting deformation calculation of the rock-fill

There are two methods for analyzing the wetting deformation of the coarse-grained materials, i, e., the "single-line method" and the "double-line method". The "single-line method" refers to the load along a certain path in the dry state. When reaching a certain stress state, the wetting saturation is progressed at the constant stress state condition, and at this moment, the increment of the deformation is the wetting deformation under this stress state, as shown in Fig. 2. However, the test work is very difficult, and the error in both the sample and test is inevitable in the "single-line method". At the same time, E_t and μ_t cannot be determined in the process of water immersion, so we choose the increment relative to the stress state to calculate.

The "double-line method" means that the coarse-grained materials are tested in the dry state and the wet state, respectively. The difference between the wet and the dry state deformation in the same stress state is used as the wetting deformation in the stress state, as shown in Fig. 3. The model parameters of two states of the "double-line method" are obtained by the triaxial shear tests under the dry and wet state conditions of the soil. Then, based on these parameters, the deformation corresponding to a certain stress state can be calculated, and the difference of two-state deformation is the deformation of the wetting state. However, the disadvantage of the "double-line method" is that the actual wetting deformation process is not in accordance with the loading path, and the wetting deformation is not taken into account under the isotropic stress state, and the wetting deformation will be small. The "double-line method" is more applicable for calculate the wetting deformation by the incremental generalized Hooke's law. Quantities E_t and μ_t of the dry sample must be determined, and the deformation is calculated before water immersion. The deformation after water immersion is calculated using E_t and μ_t of the saturated sample. The difference between these values is considered the actual water immersion deformation. Both of the plane strain or normal stress state problem can be analyzed using this method. From the above analysis, in the wetting deformation calculation, the "double-line method" is easier for calculating the wetting deformation than "single-line method". The "double-line method" is convenient for the calculation method for the finite element method, so in this paper, we choose the "double-line method" to calculate the wetting deformation of the rock-fill.

3. Results and discussion

The Maerdang Hydropower Station is the thirteenth Cascade Hydropower Station of the water project planning that is upstream of the Longyang Gorge between the Hukou and the Erduo River. The Maerdang CFRD is 211 m high, with a crest length of 342.5 m, a crest width of 12 m and a crest elevation of 3283.00 m. The wave wall is an integral structure, 5.5 m in height, and the elevation of the wave wall is 3284.20 m. The upstream dam slope gradient is 1:1.4. The setting covering and upstream blanket at an elevation of 3175.00 m both have a crest width of 5 m, and their slope gradients are 1:1.2 and 1:1.6, respectively. There are four 9-m-wide "Z"

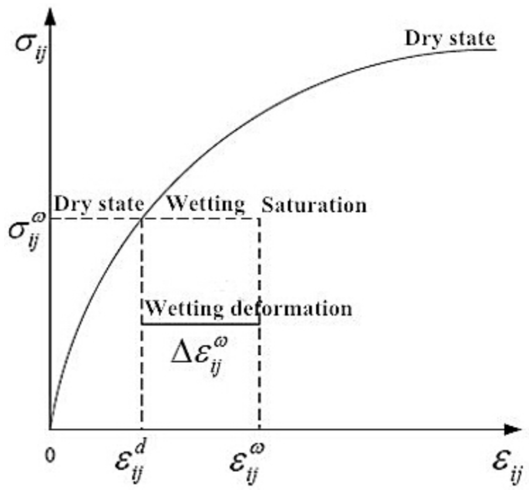

Fig. 2. Sketch for "single-line method"

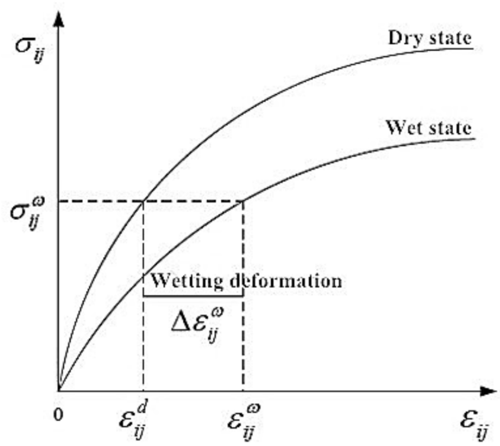

Fig. 3. Sketch for "double-line method"

shape roads in the downstream dam slope from elevation 3283.00 m to 3213.00 m, from 3183.00 m to 3200.00 m, from 3153.00 m to 3167.00 m and from 3125.00 m to 3137.00 m, respectively. Considering the earthquake protection 8 area, the slope gradient over the elevation 3233.00 m is 1:1.5, and that below the elevation is 1:1.4. The comprehensive slope gradient is 1:1.683. The dam body is divided into the upstream blanket area (1A), covering area (1B), cushion area (2A), special cushion area (2B), transition layer area (3A), rock-fill area (3BI), rock-fill area (3BII), and bank slope cushion (3C). The dam standard section and the partition area are shown in Fig. 4.

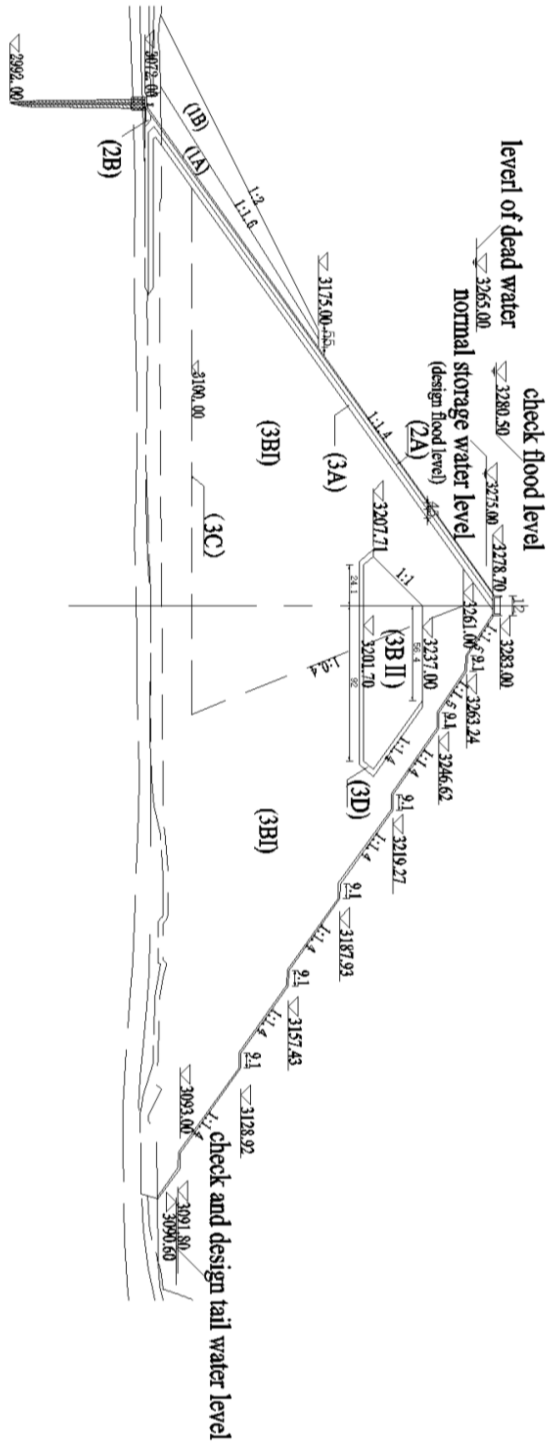

Fig. 4. Standard section of Maerdang concrete face rock-fill dam

3.1. Finite element model and parameters

Establish a three-dimensional finite element model according to the layout chart and cross-section map of the project. Then, the coordinate calculation is as follows: the creep direction is the X axis direction, the downstream reaches are the positive direction, the dam axis is the Y axis direction, and the left bank is the positive direction. The vertical Z is the plumb direction, and the upper is the positive direction. The origin of the coordinates is located on the upstream side of the right bank at the bottom of the foundation. The foundation calculation of the finite element model is as follows: along the creep direction in the upstream and downstream, respectively, extend 300 m (approximately 1.5 times the height of the dam) along the dam axis direction of the left and right banks, respectively. Extend 300 m along the depth direction. Use the spatial hexahedral eight-node element and a small amount of the six-node triangular prism unit for the discrete dam and foundation. The dam body and foundation solid model are shown in Fig. 5. Calculation boundary conditions: a boundary condition is a fixed constraint in the bottom surface of the dam foundation. Make a simply supported treatment along the Y axis in the foundation, and the left and right banks of the slope make a simple treatment. Make a simply supported treatment along the X axis in the foundation and slope of the upstream and downstream. The areas of the rest are free. The Duncan-Chang model is adapted for the model of the rock-fill material. The material parameters in dry conditions are determined by experimental data, and in wet conditions are determined by the similar engineering project. The material parameters of the dry and wet conditions are shown in Table 1 and Table 2. The face slab, wave wall, plinth, and bed rock are assumed to be linear elastic materials. The concrete grade of C30 is used to make the face slab, wave wall and plinth made with concrete of grade C25. The parameters can be checked in the Code for Design of Concrete Structures 25, and the material parameters of the bed rock are obtained by a similar engineering project. We adopted the seven-parameter creep model to calculate the creep deformation of the rock-fill. According to the experimental data, the parameters of the creep model are listed in Table 3.

Table 1. Materials for the dam of the Duncan-Chang model (E-B) parameters (Dry)

Material	ρ (kg/m^3)	K	n	R_f	φ (°)	K_b	m	K_{ur}	n_{ur}
Cushion	2240	966.3	0.44	0.61	52.4	539.3	0.35	1932.6	0.44
Transition layer	2210	1287.0	0.29	0.62	53.7	672.0	0.18	2574.0	0.29
Rock-fill 3B I	2210	1210.6	0.28	0.61	54.2	576.2	0.18	2421.2	0.28
Rock-fill 3B II	2190	1202.7	0.28	0.65	54.2	585.3	0.16	2405.4	0.28
Bank slope cushion	2240	1370.3	0.29	0.62	55.3	715.8	0.15	2740.6	0.29

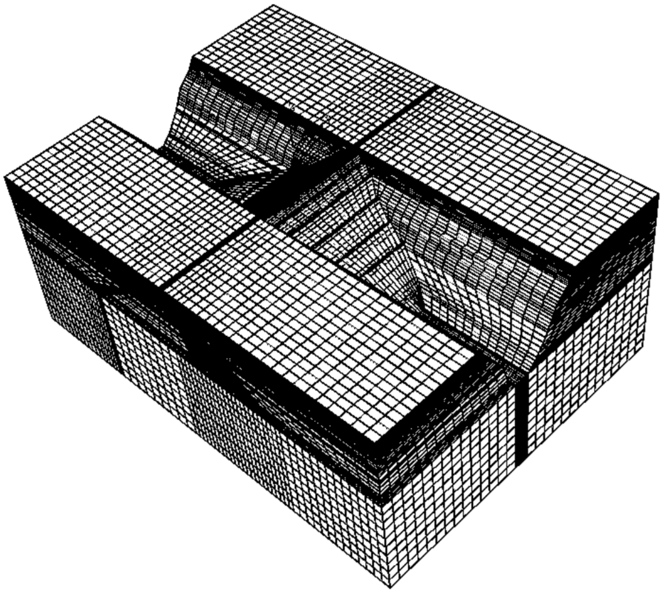

Fig. 5. FEM model of dam and its foundation

Table 2. Materials for the dam of the Duncan-Chang model (E-B) parameters (Wet)

Material	ρ (kg/m^3)	K	n	R_f	φ (°)	K_b	m	K_{ur}	n_{ur}
Cushion	2410	800	0.40	0.70	52.1	450	0.30	1600	0.40
Transition layer	2360	1100	0.25	0.70	53.4	600	0.30	2200	0.25
Rock-fill 3B I	2395	1020	0.24	0.78	50.9	500	0.30	2040	0.24
Rock-fill 3B II	2310	1000	0.24	0.82	49	510	0.40	2000	0.24
Bank slope cushion	2320	1200	0.25	0.75	46	630	0.20	2400	0.25

Table 3. Material of creep model parameters

Material	α	b	c	d	m_1	m_2	m_3
Rock-fill 3B I	0.006	0.000583	0.000148	0.00174	0.421	0.530	0.597
Rock-fill 3B II	0.007	0.000590	0.000153	0.00201	0.433	0.596	0.615
Bank slope cushion	0.005	0.000517	0.000126	0.00148	0.406	0.525	0.580

According to the construction stage, the period of construction, water storage and operation are divided into 32 loading levels for analog computation. The time of every loading level: levels 1–3 are not rock-fill; without considering its creep deformation, the input time length is 1. Level 4 means filling the rock body to an elevation of 3086 m, and the input time length is 60. Level 5 is the simulation of the construction interval, and the input time length is 75. Levels 6–10 also mean filling the rock body to be constructed to elevation 3152 m, and each level input time length is 57. Intermittent construction will be simulated in Level 11, and the input time length is 75. The rock body will be filled to an elevation of 3162 m in Level 12, and the input time length is 45. The first stage project of the face slabs will be constructed in Level 13, and the input time length is 60. Levels 14–18 mean that the filling rock body will be constructed to an elevation of 3215 m, and the input time length of every level is 48. Intermittent construction will be simulated in Level 19 again, and the input time length is 75. The rock body will be constructed to an elevation of 3225 m in level 20, and the input time length is 45. The second-stage project of the face slabs will be constructed in Level 21, and the input time length is 60. Levels 22–26 mean that the filling rock body will be constructed to an elevation of 3278.7 m, and each input time length is 48. Intermittent construction will be simulated in Level 27, and the input time length is 180. The third-stage project of the face slabs will be constructed in Level 28, and the input time length is 60. The wave wall and the downstream guardrail will be constructed in Level 29, and the input time length is 30. Water storage will be simulated in Level 31, and the input time length is 76. The conditions after two years of running will be simulated in Level 32, and the input time length is 730.

3.2. Calculation results

3.2.1. Without considering the long-term deformation. The maximum settlement of the maximum dam height profile under the time of completion is 119.4 cm, appearing at approximately 1/2 of the height of the dam. The horizontal displacement of the upstream of the dam body trend is close to the upstream, and the maximum displacement is 11.1 cm, appearing at approximately 2/5 of the height of the dam. The horizontal displacement downstream of the dam body trend is close to the downstream, and the maximum displacement is 13.4 cm, also appearing at approximately 2/5 of the height of the dam, as shown in Fig. 6. The maximum principal stress of the maximum dam height profile at the time of completion is compression stress. The maximum pressure is 2560.7 kPa, appearing at the bottom of the dam body in the middle position. The maximum pressure of the minimum principal stress is 759.9 kPa, appearing at the same position. The maximum principal stress and the minimum principal stress are both increasing with depth, as shown in Fig. 7.

3.2.2. Considering long-term deformation. Considering the long-term deformation of the rock-fill, the maximum settlement of the maximum dam height profile at the time of completion is 128.1 cm, appearing at approximately 1/2 of the height of

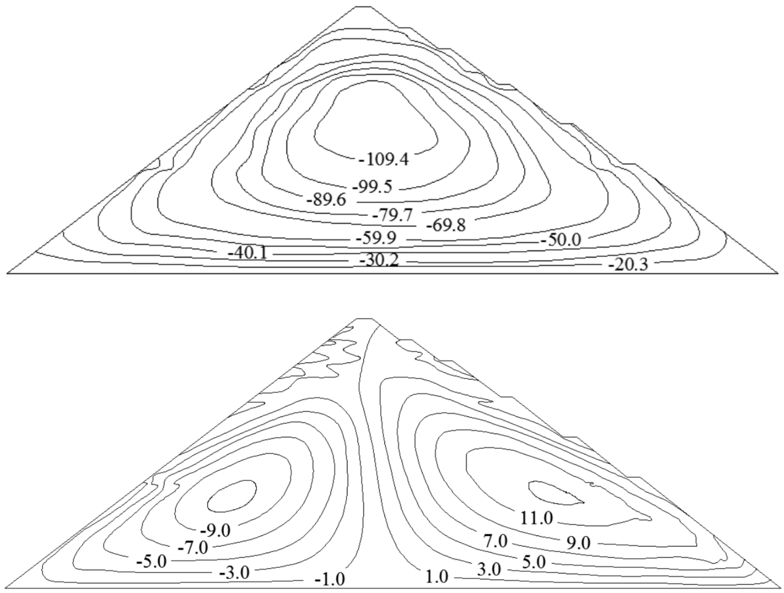

Fig. 6. Displacement contour for the section of the dam in the construction period without considering the long-term deformation (in cm): up–vertical direction, bottom–along the river direction

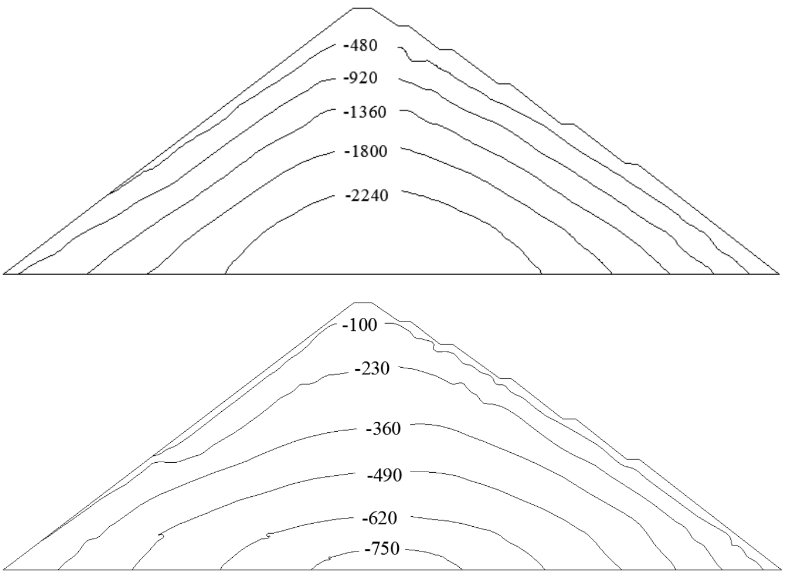

Fig. 7. Principal stress contours for the section of dam after construction period without considering the long-term deformation (in kPa): up–maximum principal stress, bottom–minimum principal stress

the dam. The horizontal displacement of the upstream of the dam body trends close to the upstream, and the maximum displacement is 14.5 cm, appearing at approximately 1/3 of the height of the dam. The horizontal displacement downstream of the dam body trend is close to the downstream, and the maximum displacement is 17.7 cm, appearing at approximately 2/5 of the height of the dam, as shown in Fig. 8. Considering the long-term deformation of the rock-fill, the maximum principal stress is also the compression stress, and the maximum pressure is 2683.4 kPa, appearing at the middle position of the bottom of the dam body. The maximum pressure of the minimum principal stress is 772.9 kPa, and it appears at the same position. The maximum principal stress and the minimum principal stress both increase with the increase in depth, as shown in Fig. 9.

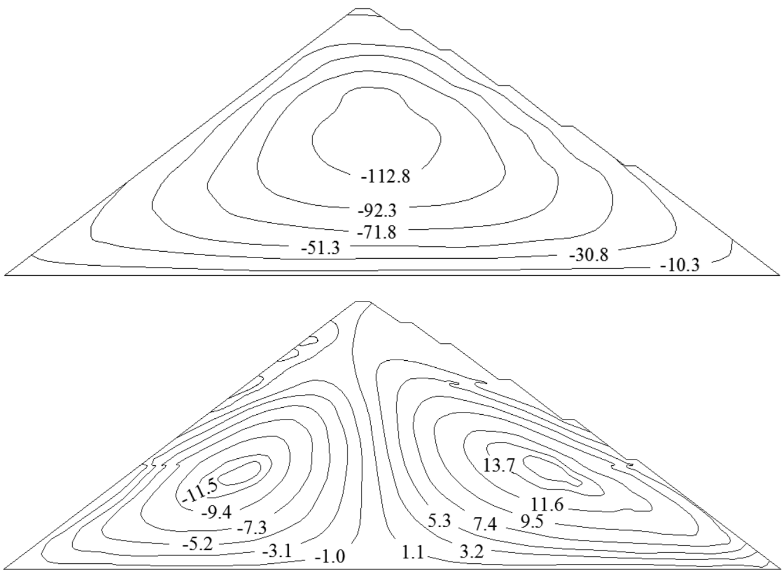

Fig. 8. Displacement contours for the section of dam in after construction period considering the long-term deformation (in cm): up–vertical direction, bottom–along the river direction

3.2.3. Comparison analysis of the calculation results. The finite element calculation results of the CFRD are summarized by considering the long-term deformation and without considering the long-term deformation, as shown specifically in Table 4.

Table 4. The effect of long-term deformation on the maximum dam height profile of Maerdang CFRD

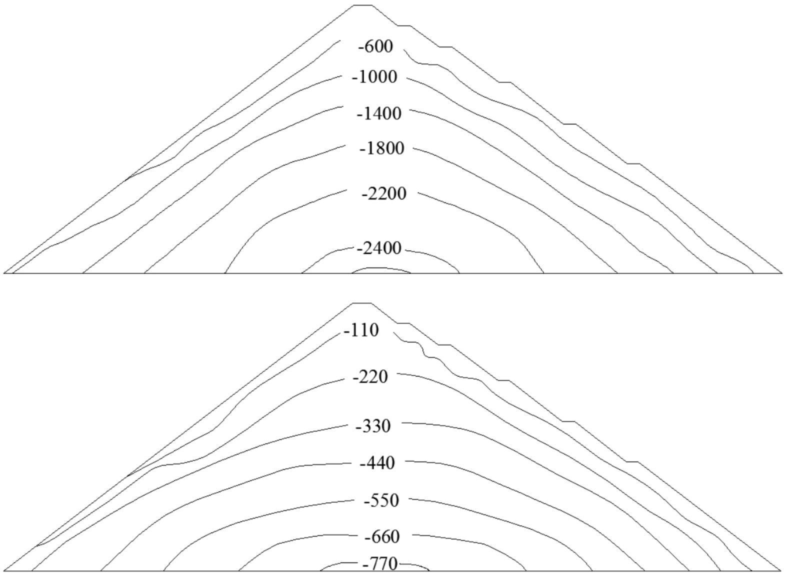

Fig. 9. Principal stress contours for the section of dam after construction period considering the long-term deformation (in kPa): up–maximum principal stress, bottom–minimum principal stress

		Displacement along the creep direction (cm)		Vertical displacement (cm)	Maximum principal stress (MPa)	Minimum principal stress (MPa)
		Upstream	Downstream			
Without long-term deformation	Time of completion	11.1	13.4	119.4	2.56	0.76
	Storage period	9.4	14.2	120.8	2.61	0.89
	Operating period	—	—	—	—	—
With long-term deformation	Time of completion	14.5	17.7	128.1	2.68	0.77
	Storage period	13.4	20.2	130.5	2.77	0.98
	Operating period	11.5	25.4	139.4	2.85	1.33

From Table 4, we can conclude that the long-term deformation of the rock-fill has effects on both displacement and stress of the maximum dam height profile. With the long-term deformation of the rock-fill, the displacement of the transverse section of the maximum dam height profile along the creep direction increases at the time of completion and the storage period. Upstream, there is an increment of displacement upward, and downstream has an increment of displacement to downward. The change in vertical displacement is obvious. The increment of vertical displacement caused by the long-term deformation at the time of completion and the storage period is 8.7 cm and 9.7 cm. Taken the long-term deformation of the rock-fill into account, the major and minimum principal stresses of the maximum dam height profile both increase at different degrees. Compared with the storage period, the displacement of the maximum height profile along the creep direction, the vertical displacement, the maximum principal stress and the minimum principal stress have increments in the operating period.

4. Conclusion

The creep deformation and wetting deformation of CFRD are calculated successfully via FEM calculation. The creep deformation and the wetting deformation of the Maerdang Hydropower Plant are analyzed. The calculation results of long-term deformation of the rock-fill is compared with the short-term deformation of the rock-fill, and the features of the long-term deformation of the rock-fill also analyzed. The main conclusions are as follows:

(1) The long-term deformation has significant influence on the stress and deformation distributions of CFRD.

(2) The stress and displacement of the dam are increased when the influence of long-term deformation is taken into account, especially in the vertical displacement of the dam.

(3) It is necessary to take the long-term deformation of the rock-fill into account for the work of design and analyses of the high CFRD. Take the long-term deformation of the rock-fill into account, a suitable settlement should be considered to ensure the safety of the dam.

References

[1] Y. S. Kim, M. W. Seo, C. W. Lee, G. C. Kang: *Deformation characteristics during construction and after impoundment of the CFRD-type Daegok Dam, Korea.* Engineering Geology *178* (2014), 1–14.

[2] L. A. Oldecop, E. E. Alonso: *Theoretical investigation of the time-dependent behaviour of rockfill.* Géotechnique *57* (2007), No. 3, 289–301.

[3] L. Gan, Z. Z. Shen, L. Q. Xu: *Long-term deformation analysis of the Jiudianxia concrete-faced rockfill dam.* Arabian Journal for Science and Engineering *39* (2014), No. 3, 1589–1598.

[4] Y. Arici: *Investigation of the cracking of CFRD face plates.* Computers and Geotechnics *38* (2011), No. 7, 905–916.

[5] J. D. Rice, J. M. Duncan: *Findings of case histories on the long-term performance of seepage barriers in dams.* Journal of Geotechnical and Geoenvironmental Engineering *136* (2010), No. 1, 2–15.

[6] B. Xu, D. G. Zou, H. B. Liu: *Three-dimensional simulation of the construction process of the Zipingpu concrete face rockfill dam based on a generalized plasticity model.* Computers and Geotechnics *43* (2012) 143–154.

[7] R. Mahinroosta, A. Alizadeh, B. Gatmiri: *Simulation of collapse settlement of first filling in a high rockfill dam.* Engineering Geology *187* (2015), 32–34.

[8] M. R. Coop, K. K. Sorensen, F. T. Bodas: *Particle breakage during shearing of a carbonate sand.* Géotechnique *54* (2004), No. 3, 157–163.

[9] G. Hunte, R. Fell: *Rockfill modulus and settlement of concrete face rockfill dam.* Journal of Geotechnical and Geoenvironmental Engineering *129* (2003), No. 10, 909 to 917.

[10] W. Zhou, J. J. Hua, X. L. Chang, C. Zhou: *Settlement analysis of the Shuibuya concrete-face rockfill dam.* Computers and Geotechnics *38*, (2011), 269–280.

[11] J. L. Justo, P. Durand: *Settlement-time behaviour of granular embankments.* International Journal for Numerical and Analytical Methods in Geomechanics *24* (2000), No. 3, 281–303.

[12] B. Y. Zhang, J. G. Wang, R. F. Shi: *Time-dependent deformation in high concrete-faced rockfill dam and separation between concrete face slab and cushion layer.* Computers and Geotechnics *31* (2004), No. 7, 559–573.

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