IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

Stress and Deformation Analysis of High Concrete Face Rockfill Dam Based on COMSOL Multiphysics

To cite this article: Runying Wang and Keping Yu 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **643** 012013

IOP Conf. Series: Earth and Environmental Science **643** (2021) 012013 doi:10.1088/1755-1315/643/1/012013

Stress and Deformation Analysis of High Concrete Face Rockfill Dam Based on COMSOL Multiphysics

Runying Wang, Keping Yu*

College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing, Jiangsu, 210024, China

*Corresponding author's e-mail: wry1164@hhu.edu.cn

Abstract. In order to study the stress and deformation characteristics of the high concrete face rockfill dam over 100 meters, in this paper, Duncan-Zhang E-B nonlinear elastic hyperbolic model is adopted, the finite element software COMSOL Multiphysics is used to establish the model and the MATLAB function is used for secondary development to analyze the stress and deformation of the concrete face rockfill dam of the Panshitou reservoir. The stress and deformation characteristics of the concrete face rockfill dam at the completion period, normal water storage condition, designed flood level condition and checked flood level condition are obtained through analysis, which provide theoretical guidance for the construction and operation of the high concrete face rockfill dam of more than 100 meters.

1. Introduction

Concrete face rockfill dam has been widely used in the world, because the face rockfill dam has the advantages of strong applicability to the environment, convenient construction, relatively low cost and good seismic performance. The deformation of the dam is a serious problem for the face rockfill dam, so it is very important to analyze the stress deformation of the concrete face rockfill dam.

At present, there is some research on stress and deformation analysis of concrete face rockfill dam. Xiangzhi Huang[1] used three dimensional nonlinear static finite element method to analyze the stress and deformation of dam body and anti-seepage body. Fuzhong Li et al.[2] used Duncan E-B nonlinear constitutive model to calculate and analyze the finite element stress and deformation of the face rockfill dam. Shuangmei Chang et al.[3] used ANSYS software and finite element method to simulate and analyze the dam. Hong Liu et al.[4] established a finite element model using ABAQUS to analyze and study the dam displacement, dam stress, slab stress. Bin Li[5] has analyzed the stress deformation of the face rockfill dam on the complex overburden layer by numerical simulation. Part of the research object is still the face rockfill dam below 100 meters, and with the continuous progress and improvement of construction technology, the height of many face rockfill dams has exceeded 100 meters. Therefore, it is of great significance to analyze the stress and deformation of high face rockfill dam. In this paper, Duncan-Zhang E-B nonlinear elastic hyperbolic model is adopted, the finite element software COMSOL Multiphysics is used to establish the model and the MATLAB function is used for secondary development to analyze the stress and deformation of the concrete face rockfill dam of the Panshitou reservoir.

The basin area of Panshitou Reservoir is 1,915 km^2, with a total storage capacity of 608 million m^3. The dead water level of the reservoir is 208.00 m and the normal water level is 254.00 m. The dam is a concrete face rockfill dam with a crest elevation of 275.70 m and a maximum dam height of 102.20 m.

2. Calculation and analysis of stress and deformation of dam body

2.1. Constitutive model of rockfill body

In finite element numerical simulation, Duncan-Zhang E-B nonlinear elastic hyperbola model is adopted for the rockfill body of concrete face rockfill dam.

The calculation formula of tangent elastic modulus is as follows:

$$E_t = K \bullet Pa \bullet \left(\frac{\sigma_3}{Pa}\right)^n \bullet \left[1\text{-}R_f \frac{(\sigma_1\text{-}\sigma_3)}{(\sigma_1\text{-}\sigma_3)_f}\right]^2 \tag{1}$$

$$R_f = \frac{\sigma_1\text{-}\sigma_3}{(\sigma_1\text{-}\sigma_3)_{ult}} \tag{2}$$

Pa is the actual standard atmospheric pressure. *K* is the modulus of elasticity. *n* is the modulus of elasticity. σ_1 is the first principal stress, σ_3 is the third principal stress (confining pressure).

According to the Mohr-Coulomb intensity criterion:

$$(\sigma_1\text{-}\sigma_3)_f = \frac{2C \cdot \cos\varphi + 2\sigma_3 \cdot \sin\varphi}{1\text{-}\sin\varphi} \tag{3}$$

c and φ are both indicators of shear strength.

The calculation formula of the volume deformation modulus is:

$$B_t = K_b \cdot Pa \left(\frac{\sigma_3}{Pa}\right)^m \tag{4}$$

K_b is the volume modulus coefficient, and *m* is the volume modulus index.

The formula of friction φ with variation of confining pressure σ_3 is as follows:

$$\varphi = \varphi_0 \text{-} \Delta\varphi \lg\left(\frac{\sigma_3}{Pa}\right) \tag{5}$$

φ_0 refers to the internal friction Angle under the condition of $\sigma_3 = Pa$.

2.2. Contact model

Goodman element without thickness is used to simulate the contact state between panel and cushion. Goodman element takes the relative displacement of corresponding nodes on both sides as variable, which can well simulate the dislocation, slip or opening of contact surface, and can consider the nonlinear characteristics of contact deformation.

2.3. Calculation of initial stress field

The initial stress state of the new filled layer is determined according to the following method:

$$\sigma_1 = \gamma h \tag{6}$$

$$\sigma_3 = K_0 \gamma h \tag{7}$$

$$K_0 = 0.95\text{-}\sin\varphi \tag{8}$$

σ_1 and σ_3 are the major and minor principal stresses at the junction of the new filled layer respectively. γ is the gravity of newly filled soil layer. *h* is the depth below the soil surface of the element centroid. K_0 is the coefficient of static lateral pressure of soil. φ refers to the internal friction angle of the material.

2.4. The solution of the fundamental equation

The method of step loading is used to simulate the actual stress-strain state in the construction process. The basic equation is solved by the load grading midpoint increment method. The load is divided into several load increments and two finite element calculations are made for each increment. Half of the load increment is first taken to find the average stress and the corresponding tangent modulus. Then it is taken as the average value of the load increment of the class, and the displacement, stress and strain increment under the action of the full load increment is solved, which is superimposed on the total displacement, stress and strain.

2.5. Computing software and its secondary development

In order to effectively simulate and evaluate the structural safety state during the dam construction and operation period of the concrete face rockfill dam, taking into account the needs of pre - and post-treatment and the secondary development of the nonlinear constitutive model of the rockfill body, the finite element calculation software of COMSOL Multiphysics was selected for the study.

In Duncan-Tensional E-B model, the tangential elastic modulus and volumetric deformation modulus of rockfill material are calculated by loading and unloading problem, and the stress state changes with each loading. Based on the COMSOL with MATLAB joint development function, the MATLAB function was used to calculate the tangent elastic modulus and the volume deformation modulus of each loading step. The corresponding tangent elastic modulus and volume deformation modulus can be obtained by automatically calling MATLAB function in COMSOL calculation.

For the calculation of the initial stress field, it is also based on the COMSOL with MATLAB joint development function, and the corresponding secondary development is carried out with MATLAB.

2.6. Finite element model

Considering the actual section structure and material partition of the concrete face rockfill dam of Panshitou Reservoir, a two-dimensional finite element model of the dam body is established. First, the superelement model was established in CAD (figure 1) , and then the CAD model was imported into the finite element software of COMSOL MULTIPHYSICS, and the extremely refined grid subdivision mode was adopted to automatically subdivide the finite element grid (figure 2) . The bottom of the dam is fixed. The total number of subdivision units is 20,792. The dam filling is divided into 11 stages. The water load is divided into 5 stages.

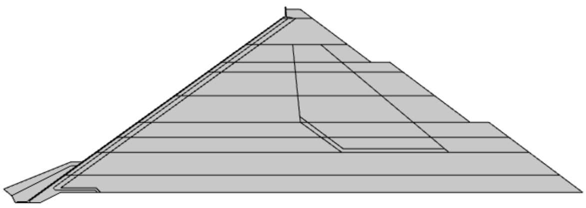
Figure 1. CAD model figure.

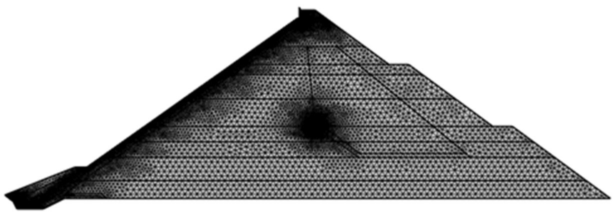
Figure 2. Finite element grid.

2.7. Calculate working conditions and parameters

The calculation conditions are shown in table 1.

Table 1. Calculation conditions.

Working condition	Condition description
QZ-1	Completion period
QZ-2	Normal water storage condition : 254.00 m upstream , no water downstream
QZ-3	Design flood level condition : 270.58 m upstream , 185.1 m downstream
QZ-4	Check flood level condition : 275.08 m upstream , 189.6 m downstream

The calculation parameters of concrete and rockfill bodies of different materials are shown in table 2.

Table 2. Calculation parameter.

Material	ρ(kg/m^3)	K	Kur	K_b	n	Rf	m	$c(Pa)$	φ(°)	$\triangle\varphi$(°)
Concrete	2350	200000		100000					45	0
Main rockfill area	2100	1050	2100	590	0.27	0.886	0.25	0	54.2	12.4
Secondary rockfill zone	2020	255	510	97	0.37	0.739	0.19	0	43.9	10.0
Cushion	2150	1050	2100	465	0.44	0.871	0.13	0	52.8	11.7
Transition layer	2150	755	1510	406	0.46	0.901	0.00	0	52.9	10.2
Waste stone slag	2000	275	550	200	0.658	0.772	0.085	0	47.4	7.5
Silty clay	1800	135	270	61	0.57	0.88	0.43	10000	28.8	0

2.8. The calculation results

The horizontal and vertical displacement nephograms and the major and minor principal stress nephograms of the rockfill body are shown in figure 3-10.

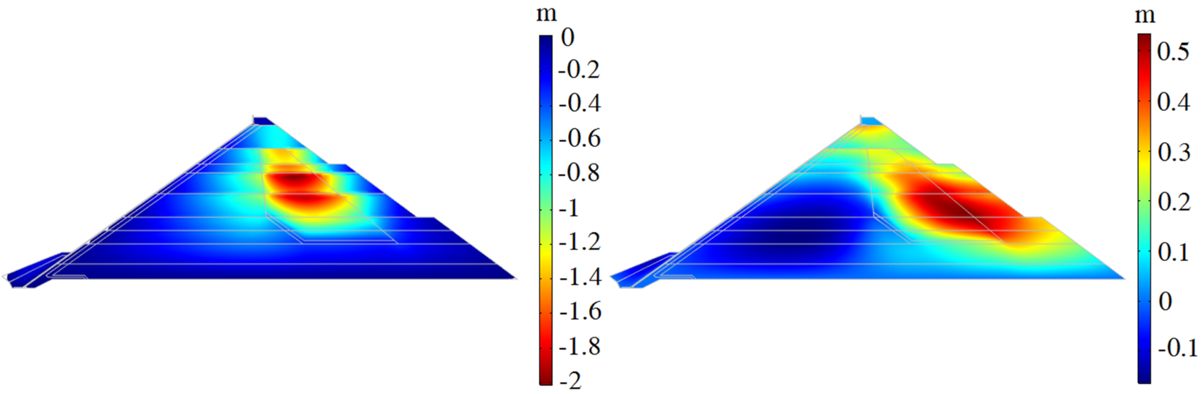

Figure 3. Nephograms of vertical displacement and horizontal displacement at completion period.

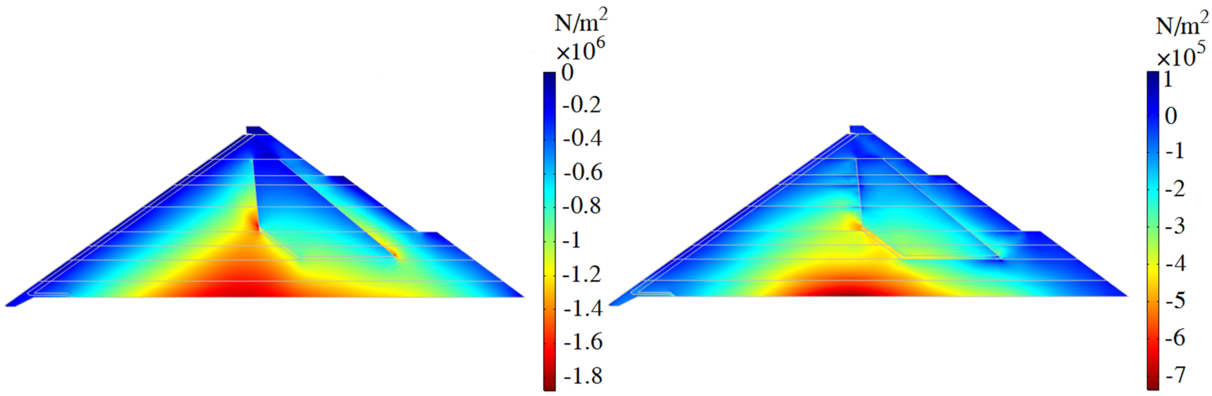

Figure 4. Nephograms of major principal stress and minor principal stress at completion period.

IOP Conf. Series: Earth and Environmental Science **643** (2021) 012013 doi:10.1088/1755-1315/643/1/012013

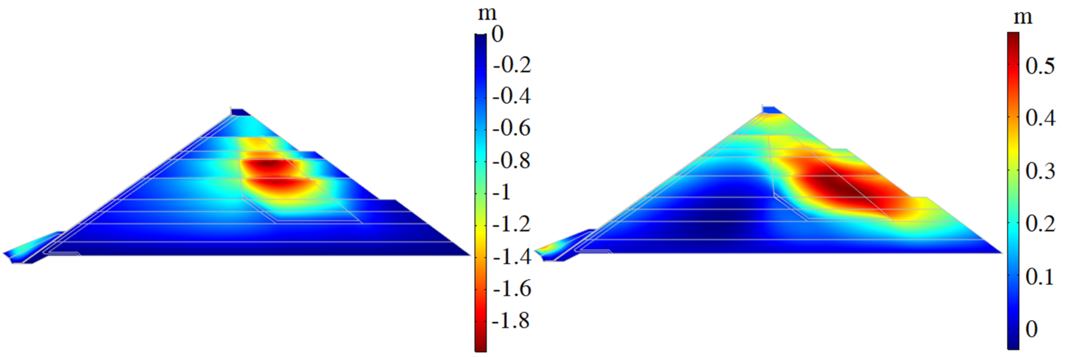

Figure 5. Nephograms of vertical displacement and horizontal displacement at normal water storage condition.

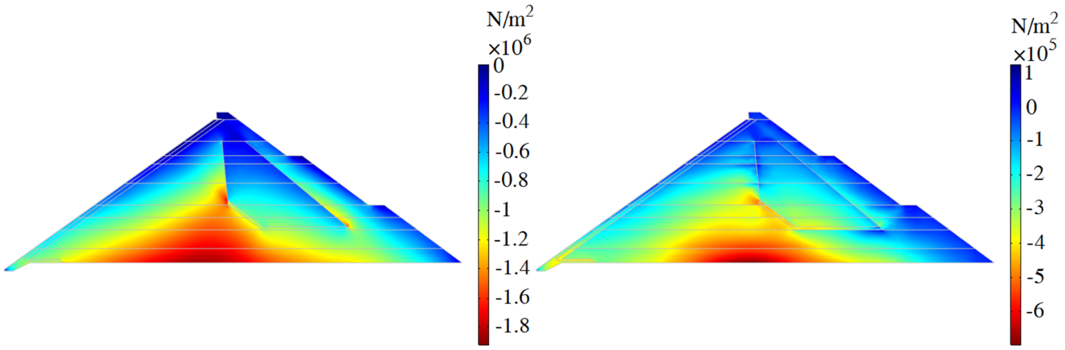

Figure 6. Nephograms of major principal stress and minor principal stress at normal water storage condition.

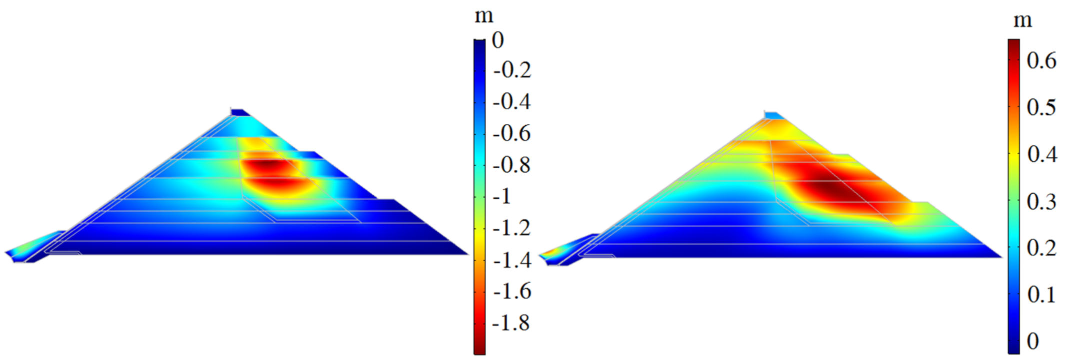

Figure 7. Nephograms of vertical displacement and horizontal displacement at design flood level condition.

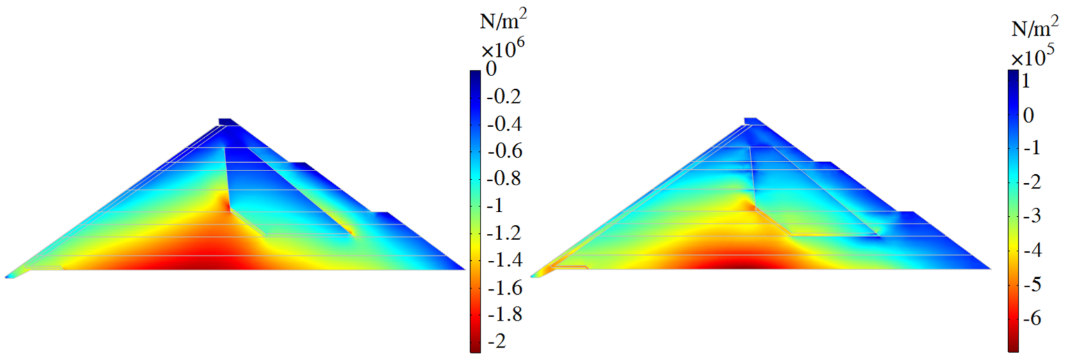

Figure 8. Nephograms of major principal stress and minor principal stress at design flood level condition.

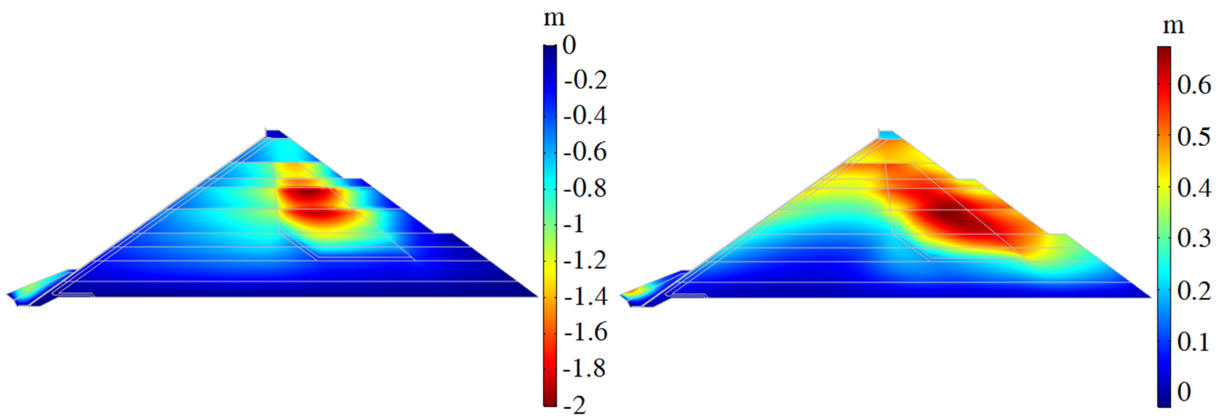

Figure 9. Nephograms of vertical displacement and horizontal displacement at check flood level condition.

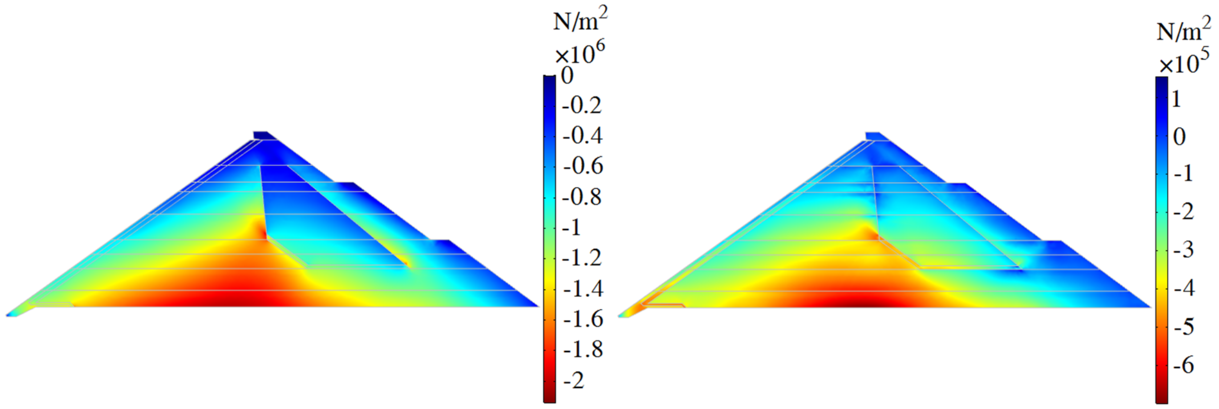

Figure 10. Nephograms of major principal stress and minor principal stress at check flood level condition.

The maximum displacement and maximum stress of the rockfill in various conditions of the dam are shown in table 3.

Table 3. The maximum displacement and maximum stress.

Working condition	Horizontal displacement(m)		Downward vertical displacement(m)	Major principal stress(MPa)	Minor principal stress(MPa)
	Upstream direction	Downstream direction			
QZ-1	0.163	0.536	2.010	1.870	0.737
QZ-2	0.040	0.562	1.990	1.920	0.697
QZ-3	0.030	0.650	1.993	2.070	0.694
QZ-4	0.028	0.674	2.000	2.140	0.697

The slab deflection at completion period is small, 10.3 cm, occurring at the elevation of the top of the blanket. Under normal water storage condition, the maximum slab deflection occurs in the middle of the slab, with a value of 34.2 cm, subsidence of perimeter joint of 1.04 cm, and opening displacement of perimeter joint of 1.18 cm. Under design flood level condition, the maximum slab deflection occurs in the middle of the slab, with a value of 31.4 cm, subsidence of perimeter joint of 1.22 cm, and opening displacement of perimeter joint of 1.30 cm. Under check flood level condition, the maximum slab deflection occurs in the middle of the slab, with a value of 53.9 cm, subsidence of perimeter joint of 1.28 cm, and opening displacement of perimeter joint of 1.36 cm.

When the water pressure acts on the face slab, the stress of face plate normal line direction basically rules is consistent, be equal to about the size of water pressure before face plate, its value is less than the compressive strength of concrete. The face slab mainly bears tensile stress along the dam slope. Under the condition of normal water storage condition, the maximum tensile stress on the face slab is 2.58 MPa except for the position near the perimeter joint, which occurs on the surface of the face slab at 194.5 m elevation. From the elevation of 258.37 m, the tensile stress below the elevation exceeds the design value of C25 concrete tensile strength. Under the condition of design flood level condition, the maximum tensile stress on the face slab is 2.86 MPa except for the position near the perimeter joint, which occurs on the surface of the face slab at 194.5 m elevation. From the elevation of 261.92 m, the tensile stress below the elevation exceeds the design value of C25 concrete tensile strength. Under the condition of check flood level condition, the maximum tensile stress on the face slab is 3.14 MPa, which occurs on the surface of the face slab at 194.5 m elevation. From the elevation of 262.27 m, the tensile stress below the elevation exceeds the design value of C25 concrete tensile strength.

3. Conclusion

Based on the joint development function of COMSOL with MATLAB, this paper carries out the secondary development with MATLAB function, and the stress and deformation characteristics of the rockfill dam under different working conditions are simulated and analyzed. The calculation results are in good agreement with practice, which indicates that the model and calculation method are scientific and reasonable, and provides a new calculation method for reference for related engineering.

The finite element calculation and analysis show that due to the soft rock material in the downstream rockfill area, the settlement of the dam is obviously inclined to the downstream from the displacement distribution of the dam. The settlement of the dam is not large, but the settlement difference between the upstream and downstream dam is large. The perimeter joint is deformed within normal range. There is no obvious shear failure zone in the dam.

According to the finite element calculation results, under the action of water pressure, the tensile stress exceeding the tensile strength of concrete will appear in the small principal stress of the panel. Therefore, the daily maintenance and monitoring of the panel should be strengthened.

References

[1] Huang, X.Z. (2018) Three - dimensional Nonlinear Static Analysis of the Stress Deformation of the Face Rockfill Dam of Xilin Reservoir. Zhejiang Hydrotechnics, 46(04):63-68+71.
[2] Li, F.Z., Si, C.L. (2019) Three-dimensional finite element analysis of concrete face rockfill dam in Maozangsi Hydropower Station. Water Resources Planning and Design, (07):114-117.
[3] Chang, S.M., Xie, L.Y. (2019) Study on Stress - Deformation of Concrete Face Rockfill Dam on Deep Overburdens under the ANSYS Software. Water Conservancy Science and Technology and Economy, 25(01):33-38+51.
[4] Liu, H., Liu, R.X. (2017) Finite element analysis on stress and deformation behavior of face rockfill dam. Water Sciences and Engineering Technology, (05):50-53.
[5] Li, B. (2019) Stress and deformation analysis of face rockfill dam on complex overburden. Water Sciences and Engineering Technology, (02):4-8.