Analysis of Stress and Deformation for concrete face rockfill dam in Downstream Reservoir of a Pumped-storage Power Station

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Abstract. Stress-deformation behavior of the concrete face rockfill dam of the construction period and filling period is simulated based on the three dimensional nonlinear finite element method and engineering situation. The three dimensional finite element method is applied, with introducing the Duncan-Chang E-B model for rockfill materials and overburden cover and Goodman element without thickness for the interface. The numerical simulation is used to Study the different rockfill materials parameters influencing the behaviour of stress-deformation of dam body. The study shows that the stress and displacement distribution regularity of the concrete face rockfill dam of the lower reservoir of the pumped storage power station within normal range, and no special adverse behavior is found. The design conform with the regulatins, and its working characteristics conform to the general law. Besides, the rockfill materials parameters have significant influence on the deformation behaviour of the dam body and face-slab.

1. Introduction
The main buildings of the lower reservoir of a pumped storage power station including the dam of lower reservoir, the sand dam at the tail of the reservoir, Spillway tunnel before flood control dam, and the empty tunnel in front of the main dam. The dam of lower reservoir uses the reinforced concrete face rockfill dam built on the bedrock with toe slab, the riverbed toe slab is built on the weakly weathered fresh bedrock, the lowest elevation of toe slab is 1686.00m, the height of dam crest is 1767.00, the corresponding dam height is 81m, and the length of dam crest is 565.2m. The crest of the dam is 10.00m wide and the upstream of the dam is equipped with a 6.20m high "L" type wave-proof wall. The height of the crest is 1768.2m and the bottom of the wall is 1762.0m. It is 1m above the normal water level, the upstream dam slope is 1:1:4 and the downstream dam slope is 1:1:4. The dam is backfilled with arbitrary materials. The height of platform top is 1767 m and the downstream slope is 1:2.0. The slope is protected by masonry. The scope is determined according to the amount of slag discarded from the lower reservoir. Curtain grouting is used to prevent seepage in the foundation of river bed and bank slope. In order to solve the problem of seepage around dam, grouting tunnels are arranged at dam abutments and curtain grouting is carried out in the tunnels. Concrete face slab, toe slab and curtain grouting form an impervious system for retaining dam of underground reservoir.
2. Numerical calculation model

2.1. Calculation model of rockfill and overburden

The rockfill and foundation overburden materials are considered as non-linear materials, and Duncan E-B model is adopted for the calculation model. The main calculation formula in the model is as follows:

$$E_1 = K_p a (1 - R_f \frac{q}{q_f})^2 \left( \frac{p}{p_a} \right)^n$$

$$K_1 = K_b p_a \left( \frac{p}{p_a} \right)^m$$

Where: $E_1$ —— tangent modulus of elasticity; $K_1$ —— tangent volume modulus; $p_a$ —— atmospheric pressure; $\sigma_3$ —— minimum principal stress; $E_3$ —— tangent modulus; $K_3$ —— tangent volume modulus; $q_f$ —— failure shear stress is determined by Mohr coulomb criterion; $p$ —— average principal stress; $q$ —— generalized shear stress; $K$, $K_b$, $n$, $m$, $R_f$ —— model parameters are determined by triaxial test.

2.2. Calculation model of concrete and bedrock

The linear elastic constitutive model is used to calculate the concrete (including wave-proof wall, face slab, bedrock and so on), which obeys the generalized Hooke's law. The parameters to be determined are severe, elastic modulus and Poisson's ratio.

2.3. Contact surface model

In order to reflect the interaction between adjacent materials with large differences in properties, the appropriate contact units are often set up between the two materials, taking the interface contact characteristics into account in the finite element analysis. Unlike ordinary solid elements, contact element is a special element that can simulate the dislocation, slippage or cracking of contact surface. Goodman element without thickness is used in the contact surface, including octahedral hexahedral thickness-free contact surface element and hexahedral pentahedral thickness-free contact surface element, which correspond to the basic element and filling element respectively.

2.4. Finite element calculation model

According to the actual situation and characteristics of the lower reservoir project of Pumped Storage Power Station, Three dimensional finite element model for dam body and dam foundation of concrete face rockfill dam with lower storehouse is established, when modeling. Regardless of the effect of excavation rebound and overburden removal, panel, cushion, rockfill and other partitions are simulated according to design size. After discretization, there are 83525 nodes and 81908 elements in the calculation model.

3. Stress and deformation analysis of dam

3.1. Displacement and stress of dam body

During the completion period, the maximum vertical displacement (settlement) of the dam body is -370.1mm, accounting for 0.46% of the maximum dam height, occurring on the downstream slope of the dam body; the maximum horizontal displacement along the valley to the upstream is -79.2mm; the maximum horizontal displacement along the dam axis to the left bank is 25.4mm, and the maximum
horizontal displacement to the right bank is -33.7mm. The maximum horizontal displacement is 111.7mm, and the maximum vertical displacement (settlement) is -385.7mm, accounting for 0.48% of the maximum dam height. It occurs near 150m and 1/2 dam height downstream of the dam axis. The maximum first principal stress is 1508.1kPa, the maximum second principal stress is 616.1kPa, and the maximum third principal stress is 607.7 kPa. Due to the influence of any material area behind the dam, the maximum principal stress of the dam body on the cross section occurs at the foot of the slope downstream from the bottom of the dam body. The maximum principal stress of any material area behind the dam is equal to the maximum principal stress of the dam body, and the distribution law is also consistent.

Under normal water level, the maximum vertical displacement (settlement) of the dam body is -375.1mm, accounting for 0.46% of the maximum dam height, occurring on the downstream slope of the dam body; under the action of water pressure, the horizontal displacement directed to the upstream decreases, and the maximum horizontal displacement decreases from 79.2 mm to 44.8 mm during the completion period; the maximum horizontal displacement directed to the left bank along the axis of the dam, for 25.9mm, the maximum horizontal displacement to the right bank is -34.5mm. In the course of water storage, the displacement of the dam increases with the increase of the water level. The maximum horizontal displacement is 112.3mm, and the maximum vertical displacement (settlement) is -390.4 mm, accounting for 0.48% of the maximum dam height. It occurs near 150m and 1/2 dam height downstream of the dam axis. The maximum first principal stress is 1525.2kPa, the maximum second principal stress is 626.4kPa and the maximum third principal stress is 612.1kPa. The maximum principal stress of any material area behind the dam is equal to the maximum principal stress of the dam body, and the distribution law is also consistent.

3.2. Stress and deformation of panel

During the completion period, because the reservoir has not yet impounded, the concrete face only bears the dead weight, so its stress and deformation is small. During operation, the deflection curves of the typical section of the panel at the normal storage level of 1761m are shown in Fig 1. As shown in Fig 1, the maximum deflection of the face slab is 196.2mm, which occurs near the middle and lower part of the deepest face slab in the valley and at the left 0+296.31 section of the pile number dam. This is in accordance with the Duncan E-B model.

![Fig. 1 Deflection of typical section of panel under normal storage level, mm](image)

Fig 2 is the slope direction stress diagram of the panel under normal water storage. As can be seen from Figure 2, due to the action of water pressure load, the bending deformation of the panel occurs. Therefore, the stress in the middle and lower parts of the panel is the largest, and the two ends are smaller. The maximum stress occurs near the middle and lower part of the deepest face slab in the valley, which is 3652.2 kPa and 0+296.31 on the left of the pile number dam.
Figure 3 shows the axial stress distribution of the dam under normal water storage. It can be seen from Fig. 3 that under normal water storage conditions, the valleys and the banks on both sides are basically compressive stress along the axis of the dam, and the maximum compressive stress occurs near the middle of the deepest part of the riverbed, and the left of the pile dam is 0+296.31, which is 678.8 kPa.

Figure 4 shows the normal stress distribution of the panel under normal water storage. It can be seen from Fig. 4 that in the normal water storage position, the normal stress of the panel increases continuously with the decrease of the panel elevation, which is basically consistent with the change of the water pressure intensity. The maximum normal stress is near the bottom of the panel, and the maximum value is 793 kPa. The law of stress variation conforms to the laws of mechanics.

3.3. Panel seam and peripheral seam displacement

The panel is under the normal water level, the panel joint in the middle of the river bed is in a squeeze state, and the panel joints near the bottom of the two banks and some panels are in tension. The maximum displacement of the panel seam is: the shear displacement of the slit is 13.0 mm, and the vertical seam shear displacement maximum is close to 0, so that the panel is not displaced, and the tensile displacement of the seam is 10.0 mm. It can be seen that the deformation of the panel seam is not large.
The surrounding seam is under the normal water level, the left and right bank slopes are mostly in tension, and the opening displacement is very small. As the river bed approaches, the opening displacement gradually increases, and close to the central part of the river bed, these surrounding areas The slit opening displacement is slightly smaller than the two sides; the slope is steeper, the deformation of the surrounding seam is larger, the slope is gentler, and the deformation of the peripheral seam is smaller. The maximum displacement of the peripheral seam is: the shear displacement of the slit is 15.0 mm, and the vertical seam shear displacement 20.0mm. It can be seen that the deformation of the surrounding seam is large, and necessary engineering measures must be taken to prevent the joint water from being damaged due to excessive deformation of the joint.

4. Influence of rockfill parameters on working behavior of dam

In order to consider the uncertainty of dam body filling construction, the influence of different dam material parameters on the working behavior of dam body is studied, and the sensitivity analysis of construction dam control parameters is carried out. The main parameters K and Kb of the Duncan-Zhang model of the dam are increased by 10%, reduced by 10% and reduced by 20%, respectively. The calculation results of stress deformation of the dam under the normal water storage level are shown in Table 1.

Through the comparative analysis of Table 1, it can be found that the deformation modulus coefficient of the dam material is reduced, the overall mechanical properties of the rockfill body are relatively deteriorated, and the deformation modulus is decreased. Therefore, the deformation of the dam body is increased, but the influence of the modulus reduction on the stress is obtained. Smaller. At the same time, the mechanical parameters of the dam have a great influence on the stress and deformation characteristics of the entire dam and the panel. The compactness of the rockfill material is increased, and the modulus coefficient is large, the deformation of the dam body is small, and the deformation and stress of the panel are also reduced. Therefore, it is advantageous to increase the compactness of the rockfill body. In addition, the cushion material should have a high shear strength.

Table 1. Summary of sensitivity analysis calculation results

| Calculation condition                      | Normal storage level | Dam body displacement (mm) | Dam body stress (kPa) |
|-------------------------------------------|----------------------|---------------------------|----------------------|
|                                           | Original parameter   | Deformable modulus Increase by 10% | Deformable modulus Reduce 10% | Deformable modulus Reduce 20% |
| Horizontal displacement along valley      |                      |                           |                      |
| Upstream                                  | 44.8                 | 35.6                      | 44.1                 | 49.8                  |
| Downstream                                | -                    |                           |                      |
| Horizontal displacement of dam axis       |                      |                           |                      |
| To the left bank                          | 25.9                 | 25.1                      | 27                  | 28.3                  |
| To the right bank                         | 34.5                 | 33.4                      | 35.6                | 37.4                  |
| vertical displacement down                | 375.1                | 355.6                     | 396.7               | 433.2                 |
| First principal stress                    |                      |                           |                      |
| Compressive stress                        | 1525.2               | 1525.0                     | 1525.8              | 1526.1                |
| Second principal stress                   |                      |                           |                      |
| Compressive stress                        | 626.4                | 625.5                      | 627.6               | 628.9                 |
| Third principal stress                    |                      |                           |                      |
| Compressive stress                        | 612.1                | 611.3                      | 614.2               | 615.6                 |
5. Conclusion
This article takes the actual project of the rockfill dam of a pumped storage power station as an example. The comparative system analyzes the effects of the working form and rockfill parameters of the dam on the stress and deformation of the whole dam and the panel. With the analysis, the following main conclusions were obtained:

1) The Duncan E-B model can reasonably reflect the working behavior of the dam in different periods, and calculate the stress and deformation behavior of the reservoir basin and the face dam under different working conditions, and the construction period and operation period. The safety of the reservoir is evaluated to reflect the nonlinearity of the rockfill during damming and storage. The calculated displacement and stress distribution of the dam conforms to the general law.

2) Under the action of water pressure, part of the panel joint in the central part of the riverbed is in a state of being squeezed, and the panel joints on both sides of the river are in a stretched state. Therefore, it is necessary to arrange the design panel seams reasonably according to the calculated panel seam deformation results.

3) The mechanical parameters of the dam material have a great influence on the stress and deformation characteristics of the entire dam body and the panel. The compactness of the rockfill material is increased, and the modulus coefficient is large, the deformation of the dam body is small, and the deformation and stress of the panel are also reduced. Therefore, it is advantageous to increase the compactness of the rockfill. In addition, the cushion material should have a certain shear strength to prevent excessive compressive stress and misalignment between the panels.

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References
[1] Cen Weijun, Zhu Yueming, Wu Kui, Wu Jicai, analysis for stress and deformation of concrete facing Rockfill Dam of Pumped-storage Power station. Water Resources and Power, 2004, 22 (3): 26-29.
[2] Diao Zhiming, Deng Wenjie, Liu Liangjun, Wang Junjie, 3D FEM Analysis of Stress and deformation of Jinfoshan Concrete Facing Rockfill Dam. Water Resources and Power, 2013, 31 (1): 61-64.
[3] Xie Xiaohua, Li Guoying, stress-deformation analysis of Chengping concrete-faced rockfill dam. Chinese Journal of Geotechnical Engineering, 2001, 23 (2): 243-246.
[4] Wen Lifeng, Chai Junrui, Wang Xiao, Stress-deformation behavior of a concrete-faced rockfill dam with a deep overburden foundation. Rock and Soil Mechanics, 2015, 36 (8): 2386-2394.
[5] Chang Shuangmei, He Wenshe, Chang Zhoumei, Zhang Shuo, analysis of stress and deformation of High Concrete Faced Rockfill Dam Based on Stage Loading. South-to-North Water Transfers and Water Science & Technology, 2013, 11 (6): 93-97.
[6] Gu Ganchen, Huang Jinming, analysis of Stresses and deformation of Concret-face Rockfill Dam. Journal of hydroelectric engineering, 1991, 1 (32): 12-23.
[7] Pan Jiajun, Fei Sheng, analysis of Stress and Strain for CFRD by 3-D nonlinear FEM. Water Resources and Power, 2007, 25 (2): 39-41.
[8] Liu Mengcheng, Gao yufeng, Liu hanlong, finite element analysis of long-term stress-deformation behavior for concrete-faced rockfill dam. Rock and Soil Mechanics, 2010, 31 (1): 412-418.