Numerical simulation and operation characteristics analysis of folded line concrete face rockfill dam: case study of Yimeng Pumped storage power station

Qiang Ren*, Guoying Li¹ and Kuangmin Wei¹
¹Nanjing Hydraulic Research Institute, University, Nanjing, Jiangsu, 210024, China
*Corresponding author’s e-mail: qren@nhri.cn

Abstract. Take Yimeng pumped storage project as a case of a folded-line concrete face rockfill dam, three-dimensional static finite element stress and deformation analysis is carried out to simulate the characteristics of the dam during construction and storage period, the deformation mechanism of the folded-line concrete face rockfill dam is analysed, and the stress and deformation law of the folded-line concrete face dam is obtained. The analysis shows that the large turning angle of panel is the most obvious factor to increase tensile trend and degree of face slabs and peripheral joints, the connecting plate has contribution to the improve stress and deformation behavior of slabs and peripheral joints. It is suggested to strengthen the research on the tensile properties of the slabs, the connection plate and the waterproof structure.

1. Introduction
Concrete faced rockfill dams (CFRD) have been widely used in the design of pumped storage power station project. One of the problems associated with the power station at mountainous areas is complex topography and geology. Considering this problem, irregular design scheme such as folded line CFRD scheme[1,2] will be promoted to optimize dam layout design, increase reservoir capacity, reduce the dam height, and create favourable conditions for the layout of adjacent buildings. As a case study, this paper chooses Yimeng Pumped storage power stations, with a folded line design scheme, to analyse the deformation mechanism and provide reasonable suggestions for dam construction [3].

2. General situation of engineering
YIMENG CFRD with a height of 78.6m from the river bed is located in Shandong province; it is a Pumped storage power stations,whose main objective is electricity generation. Yimeng dam is 223.6m in crest length, oriented in 56° direction, 10m in crest width and 10255800 m³ in volume. The materials in constructing compacted rockfill dams are cushion materials(2A), transitional rockfill(3A), main rockfill materials (3B), downstream rockfill materials (3C), and slag heap at the dam toe (4D). General layout and the Typical cross section of the dam are displayed in Fig. 1 and Fig 2.
3. Calculation parameters and simulation

3.1. Calculate model and parameters

Three dimensional total stress finite element method was used. Duncan E-B model is adopted in static calculation model of rockfill, which can better reflect the nonlinear characteristics of rockfill material for dam construction [4-7]. The model parameters are determined according to triaxial tests on specimens prepared from each zone. The model parameters are listed in Table 1.

Table 1. Parameters of rockfill materials.

| Setting | $\rho$ (g/cm$^3$) | $c$ (kPa) | $\varphi_0$ (°) | $\Delta\varphi$ (°) | $K$ | $n$ | $R_\ell$ | $K_b$ | $m$ |
|---------|-----------------|-----------|-----------------|-------------------|-----|-----|----------|-------|-----|
| 2A      | 2.15            | 0         | 52.9            | 8.5               | 1072.5 | 0.33 | 0.67      | 481.7 | 0.27 |
| 3A      | 2.12            | 0         | 51.6            | 8.6               | 1044.5 | 0.30 | 0.67      | 454.2 | 0.22 |
| 3B      | 2.07            | 0         | 49.6            | 8.2               | 979.1  | 0.27 | 0.66      | 411.1 | 0.09 |
| 3C      | 2.09            | 0         | 50.4            | 8.7               | 1016   | 0.27 | 0.67      | 426.6 | 0.15 |
| 4D      | 1.98            | 0         | 40.0            | 9.0               | 400    | 0.33 | 0.65      | 245   | 0.13 |

The concrete structure is composed of C25 concrete with axial compressive and tensile strengths of 16.7 MPa and 1.78 MPa, respectively. Linear elastic model is used to simulate concrete face slabs and connecting plates, the parameters of which are presented in Table 2.

Table 2. Model parameters of concrete structure

| Model         | Density(g/cm$^3$) | Elasticity moduli(GPa) | Poisson’s ratio |
|---------------|-------------------|------------------------|-----------------|
| Mohr-Coulomb  | 2.5               | 28                     | 0.167           |
Goodman contact surface element is used between the face slab and the cushion. The contact surface model parameters are determined by analogy with other engineering test data. The peripheral joints are simulated by connection element, and the vertical joints of the face slab are simulated by separation joint model.

3.2. Finite-element model and boundary conditions
The entire three-dimensional finite element model of the dam is shown in Fig.3, the rockfill materials and slabs were simulated by spatial 8-node isoparametric elements, with a total of 13,742 nodes and 11,792 elements. The Numbers of element follow the dam construction sequence to simulate the dam construction process. The thickness of each layer was less than 8 m. The face slab grid is shown in Fig.4.

The bottom boundary of the dam was fixed in the x, y and z directions. Gradual loading is adopted to simulate the effect of the filling of the reservoir. The water pressure was simulated as a surface force on the face slabs. The embankment construction is simulated in 26 stages and the water inflowing is simulated in 14 stages with 5 m from reservoir bottom to normal pool level.

![Three-dimensional finite element mesh of the dam](image)

**Fig.3** Three-dimensional finite element mesh of the dam

![Grid of the face slab](image)

**Fig.4** Grid of the face slab

4. Calculation results and analysis

4.1. Dam deformation analysis
The deformation distribution of largest cross section in the completion period exhibited in Fig. 5. It can be concluded that negative values indicate that deformations are toward the upstream, while the positive values indicate that deformations are toward the downstream. The maximum value to the upstream and downstream are respectively 8.6cm, 5.6cm. The maximum settlement occurred at the middle height of the dam, with a value of 29.4cm.

The displacement in the max section under water pressure showed in Fig.6. It shows that the lateral displacements tend toward the downstream side, displacements in the upstream gradually decreased to 3.9cm, while displacements in the downstream increased to 7.1cm. The maximum settlement increased to 30.3cm, account for about 0.39% of the entire dam height. The deformation distribution and magnitude of dam accords with the general characteristics of deformation of earth-rockfill dams.
4.2. Analysis of Face Slab Stress and Deformation

The stress and deformation states after the casting of slabs were used as the initial state in the analysis. The simulated along-axis deformation and deflection of slabs at the time of completion of full storage is plotted in Fig.7.

It can be seen that axial deformation has a tendency of extrusion to the center of the valley. The deformation of slab mostly expressed in left slab, left and right displacement is 0.54cm and 0.52cm respectively. The maximum deflection of left slab is 7.7cm while right slab is 2.4cm. The values of deflection were in the normal range.

Fig.8 illustrates the contours of the slab stresses along the axis direction and the slope. The slab mostly presented as pressured state, the maximum along-axis compressive stress occurred in the middle of the left slab, with a value of 5.77MPa. The tensile stress mainly distributed near the side of the bank and connecting plate around, the maximum stress is 1.04MPa.
Based on the numerical results, the following conclusions can be made:

4.3. Displacements of peripheral joints

The peripheral joint displacement of slabs and connecting plate is shown in Fig.9. The dislocation of perimeter joints towards river bed, and the maximum dislocation is located on the right bank, with a value of 8.4mm. The Settlement of perimeter joints towards inner dam, the maximum settlement located near the riverbed is 12.1mm. Except the bottom of the face slabs, the opening of perimeter joints are in tension, and the magnitude of which related to topography, the maximum opening value of the left slab is 11.4mm, while value of the right slab is 6.2mm.

The deformation distribution of peripheral joints was able to satisfactorily describe the deformation and stress trends of slab and connecting plate. The tensile areas are mainly with tensile joints, while the compressive stress area is mainly compressive joints. The deformation value of structural joints is in the range of bearable water-stop strips.

5. Discussion and conclusions

As a case study, Yimeng dam is typical fold-type face rockfill, which provides an opportunity to verify the design scheme and safety evaluation procedures for high CFRDs. In this paper, 3D numerical analysis of Yimeng CFRD during the construction, impoundment stages are carried out with the static finite element. The stress and deformation distributions are analysed and compared. Based on the numerical results, the following conclusions can be made:

- The settlement of the dam is basically consistent with the measured value of similar projects; the tensile and compressive stresses of the face are within the allowable range of concrete material strength, and the displacement of the surrounding joints is within the tolerable range of the watertight structure. The dam is good enough to meet the normal operation of the dam and the design is reasonable.
- Numerical results indicate that large turning angle of face slab is the most factor to increase tensile trend and degree of face slabs and peripheral Joints, the connecting plate has some contribution to the improve stress and deformation behavior of slabs and peripheral joints, increase the compatibility between the bending line and surrounding deformation and reduce the sudden change of stress;
- Appropriate measures for controlling the tensile stresses of slabs around folding areas may be necessary in the design of CFRDs.
Acknowledgments
The authors gratefully acknowledge the support provided by the National Key R&D Program of China(NO.2017YFC0404904,NO.2018YFC1808503),the Joint Fund of the National Natural Science Foundation of China and Yalong River(NO.U1765203).

References
[1] Wang D Y, CHEN Z W, TANG Y Q (2011) Behaviours of high broken line concrete face rock-fill dam of Bashan Hydropower Station. Chinese Journal of Geotechnical Engineering, 33: 1483-1488
[2] He Y L, Luo J (2003) Analysis of Deformation and Stress of A Piecewise CFRD. Chinese Journal of Hong Shui He, 4: 18-23
[3] MA H Q, CAO K M (2003) Key technology of upper-high CFRD. Chinese Journal of Engineering Sciences, 9: 4-10
[4] YANG Z Y, ZHOU J P, JIANG G C, et al (2011) Development of concrete faced rockfill dams in China, Chinese Journal of Water Power, 37: 18-23.
[5] LI N H, YANG Z Y (2012), Technical advances in concrete face rockfill dams in China, Chinese Journal of Geotechnical Engineering ,34:1361-1368
[6] LI N H (2011) New concept of design for high concrete face rockfill dams, Chinese Journal of Engineering Sciences, 13:12-18+28
[7] ZHOU M Z, ZHANG B Y, WANG W (2016) Algorithm and simulation methods for the soft longitudinal joint of the concrete faces in high concrete-faced rockfill dams, Chinese Journal of Rock Mechanics and Engineering, 35 Supp.1: 2806-2013