3D Finite Element Analysis of Yixing CFRD Built on Inclined Mountain Slope

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Abstract: There are few CFRDs built on steep slope with dam height more than 50 m. So does the relative design and construction experience. The 75 m-high Yixing CFRD was built on steep mountain slope and the 45.9m-high gravity retaining wall was used to against dam sliding. Since the excessive deformation of dam body and perimetric joints would lead to failure of seal materials and cause water leakage, 3D nonlinear finite element stress-deformation analysis was carried out. 3D finite element mesh with 63875 elements including retaining wall and surrounding mountain was established by use of advanced grid discreteness technique. Large scales of equations solving method were adopted in the computer procedure and the calculation time was greatly reduced from former 40 hours to now 45 minutes. Therefore the behavior of the dam, retaining wall and the joint was obtained in a short time, and the results would be helpful to the design and construction of Yixing dam.

1. Introduction

The concrete-faced rockfill dam (CFRD), as a competitive dam style and full of life-force, is widely used in China in recent years [1-2]. However, there are few CFRDs built on inclined mountain slope with dam height more than 50 m. So does the relative design and construction experience. Yixing pumped storage power station is located in the Tongguanshan District. It is about 7km southwestern suburb of Yixing City, Jiangsu province, China. The total installed capacity of the power station is 1000MW. Yixing CFRD is built on the inclined mountain slope and it is a very important part of pumped storage power station. The maximum height of the dam is 75m, the length of dam is 494.9m. To anti-sliding and ensure the stability of dam, the gravity retaining wall with maximum height 45.9m was used.

2. 3D Mesh Generation

The influence of the dam foundation and the surrounding mountain on the stress and deformation of CFRD and retaining wall is considered. In this calculation, the scope of the three-dimensional mesh includes not only the CFRD and gravity retaining wall, but also the dam foundation and the right side and left side mountains.

The self-written finite element mesh generation program is used to generate the 3D mesh. According to CAD files such as three-dimensional topographic map, two-dimensional geological profile and two-dimensional dam standard cross-section map provided by design institute, topographic map of foundation excavation Provided by the construction unit, the 3D finite element mesh is generated.

The main element type of the dam is 8 nodes hexahedral isoparametric element. 6 nodes tri-prism
elements and 4 nodes tetrahedron elements are adopted also. The total number of elements is 63875, the total number of nodes is 65286.

The three dimensional topographic map of foundation is shown in figure 1. The mesh of topographic map of dam foundation is shown in Figure 2. The 3D finite element mesh of dam foundation is shown in figure 3. The rendered mesh of retaining wall is shown in figure 4.

The layer by layer construction process of dam is considered by 40 steps and the water storage process is simulated as 10 steps, for total of 50 steps main increment is adopted. In order to improve the calculation accuracy, the main increment of each step is divided into 2~3 sub-increments at each load step. The typical mesh section is shown in figure 5.

3. Constitutive models

3.1 Linear elastic model
Linear elastic model is used to simulate the behavior of Concrete face slab, toe slab, retaining wall. The concrete parameter is: density \( \rho = 24.5 \text{kN/m}^3 \), Poisson ratio \( \gamma = 0.167 \). The elastic modulus of concrete face slab and toe slab is: \( E = 31,500 \text{ MPa} \), the elastic modulus of concrete retaining wall is \( E = 20,000 \text{ MPa} \).

3.2 Duncan-Chang Nonlinear elastic model
Duncan-Chang Nonlinear elastic model[3] is a typical constitutive model for coarse–grained material and is widely used in China to analysis of stress and deformation of earth dam and CFRD. The elastic modulus of the model is a function of the stress state, which can be used to describe the nonlinear and compressive strength of the stress-strain relationship. The model can be used for the loading and unloading of coarse-grained materials, which use nonlinear elastic to partly describe the elastic-plastic deformation of coarse grained materials. Following formula is used:

\[ E_t = \left[ 1 - R_f \left( \frac{1 - \sin \phi}{2c} \right) \left( \frac{\sigma_3 - \sigma_1}{\sigma_3 \sin \phi} \right)^2 \right] k \left( \frac{\sigma_3}{P_a} \right)^n \]

\[ B_t = k_b P_a \left( \frac{\sigma_3}{P_a} \right)^m \]

(1)

Where \( E_t \) is the tangent elastic deformation modulus, and the \( B_t \) is the bulk modulus, and \( P_a \) is standard atmospheric pressure.

For unloading and re-loaded, \( E_{ur} \) substitutes \( E_t \) in equation (1):

\[ E_{ur} = k_{ur} P_a \left( \frac{\sigma_3}{P_a} \right)^n \]

(2)

Coarse-grained materials internal friction angle \( \phi \) with the compressive stress change is given by equation(3).

\[ \phi = \phi_o - \Delta \phi \left( \frac{P}{P_a} \right) \]

(3)

The material parameters in equation (1) to (3), such as \( k, k_b, k_{ur}, R_f, c, \phi_o, m \) and \( n \) can be obtained from large scale tri-axial test.

Duncan-Chang E-B model was used here to prediction Yixing dam behavior. The parameters shown in table 1 was obtained by tri-axial test.

| Material Name          | \( \gamma_d \) (kN/m³) | c (kPa) | \( \Phi \) (°) | \( \Phi_o \) (°) | \( \Delta \Phi \) (°) | K | n | \( R_f \) | \( K_b \) | m | \( K_{ur} \) |
|------------------------|-------------------------|--------|-------------|-------------|-----------------|---|---|---------|---------|---|----------|
| Bedding layer          | 21.7                    | 198    | 40.2        | 56.9        | 13.5            | 1080 | 0.48 | 0.75    | 250     | 0.35 | 2K |
| Main rockfill Zone 1   | 21.7                    | 156    | 40.2        | 53.1        | 8.5             | 715  | 0.34 | 0.86    | 270     | 0.28 | 2K |
| Main rockfill Zone 2   | 21.7                    | 154    | 42.1        | 55.1        | 8.9             | 800  | 0.44 | 0.86    | 450     | 0.42 | 2K |
| Transition Zone        | 21.9                    | 133    | 43.7        | 52.2        | 6.5             | 1090 | 0.47 | 0.73    | 250     | 0.37 | 2K |

3.3 Desai thin layer element

The interaction between dam rockfill and concrete face slab and the interaction of rockfill dam and concrete retaining wall was simulated by Desai thin layer element[4]. It is a effective technology to avoid the stress concentration during the stress and deformation calculation. The basic formula is shown as follows:

\[ \tau_s = \lambda_s \Delta u \]

\[ \sigma_n = \lambda_n \Delta v \]

(4)
where $\tau_s$ is shear stress and $\sigma_n$ is normal stress.

| $R_f$ | $K_1$ | $n$ | Force         | $\delta /$ | $C$ (kPa) |
|-------|-------|-----|---------------|------------|-----------|
| 0.76  | 4800  | 0.54| compression    | 60000000   | 36        | 0.0       |
|       |       |     | extension     | 100        | 3         | 0.1       |

### 3.4 Joints element model

Joints element model is used to simulate the vertical joints deformation between the face slab-face slab, face slab-toe slab, face slab-mountains. The equation is listed as:

$$
\begin{bmatrix}
\tau_{yx} \\
\sigma_{yy} \\
\tau_{yz}
\end{bmatrix} =
\begin{bmatrix}
k_{yx} & 0 & 0 \\
0 & k_{yy} & 0 \\
0 & 0 & k_{yz}
\end{bmatrix}
\begin{bmatrix}
\delta_{yx} \\
\delta_{yy} \\
\delta_{yz}
\end{bmatrix}
$$

\( \tau_{yx} \) — Longitudinal shear stress of joint connection element;

\( \sigma_{yy} \) — Tension stress of joint connection element;

\( \tau_{yz} \) — The vertical shear stress of the joint connection element;

\( \delta_{yx}, \delta_{yy}, \delta_{yz} \) — The displacement of peripheral joints in shear direction, tensile direction and settlement direction;

\( k_{yx}, k_{yy}, k_{yz} \) — Stiffness coefficient.

### 4. Calculation results

#### 4.1 Deformation of dam body

Deformation of dam body is listed in table 3. The maximum vertical settlements during construction and water storage period are all approximately appeared at the 1/3 height of dam body. At the first filling of the reservoir, the maximum vertical settlement is 22.0 cm and the maximum horizontal downstream displacement is 10.3 cm.

| Displacement(cm) | Water elevation (m) | Horizontal | Vertical settlement |
|-------------------|---------------------|------------|---------------------|
|                   |                     | Downstream Displacement | Upstream Displacement | |
| Completion of construction | 9.2 | 2.0 | 20.0 |
| impoundment       | 10.3 | 0   | 22.0 |
Figure 6. Vertical settlement at the completion of construction (Unit: cm)

Figure 7. Vertical settlement after impoundment (Unit: cm)

Figure 8. Horizontal displacement at the completion of construction (Unit: cm)

Figure 9. Horizontal displacement after impoundment (Unit: cm)
4.2 Deformation and stress of face slab
The maximum deformation of face slab is listed in table 4 and shown in figure.10– figure11.

| Normal of face slab (deflection) | Slope Direction | Axial direction |
|---------------------------------|-----------------|-----------------|
| 6.7                             | 2.1             | 0.2             |

![Figure 10. Face slab defection after impoundment (Unit: cm)](image1)

![Figure 11. Face slab axial displacement after impoundment (Unit: cm)](image2)

Table 5 Maximum stress of face slab after impoundment (Unit: kPa)

| Direction     | Tensile Stress | Compressive Stress |
|---------------|----------------|--------------------|
| Slope Direction | -200           | 300                |
| Axial direction | -30            | 30                 |

Most of the stress along slope direction of face slab is compressive stress, but the face slab zone adjacent to the surrounding mountain is tensile stress. Axial stress is mainly compressive stress, the maximum compressive stress 300kPa is located at the concave part of mountain gully. However, the zone adjacent to peripheral joints is tensile stress too.

4.3 Deformation of joints
The maximum value of deformation of joints is listed in table 6.
Table 6 Maximum deformation of joints (unit: mm)

| Joints name       | Opening Along dam axis | Compression Along dam axis | Settlement Vertical to face slab | Shearing Along zone between face slab-mountain |
|-------------------|------------------------|-----------------------------|---------------------------------|-----------------------------------------------|
| vertical joints   | 0.6                    | 0.33                        | 1.72                            | 1.32                                          |
| perimeric joints  | 0.9                    | 0.59                        | 2.07                            | 2.28                                          |

4.4 Retaining wall stability results

3 typical sections were chosen to analysis the retaining wall stability and 7 working conditions were analysis for each typical section. The calculation results shown that all the safety factor satisfied the regulation requirements. Figure 12 is representative smallest safety factor in all computed 21 calculated working conditions.

![Figure 12. stability analysis result of retaining](image)

5. Conclusion

According to the calculation results, the stress-deformation of dam body, the stress-deformation of face slab, opening of joints are all within the reasonable scope. Moreover, the total settlement of rockfill is close to 0.3% dam height.

The gravity retaining wall is safe and the worried sliding problem will not happen after the complement of dam.

All in all, after the filling of water, the safety of dam will be guaranteed. The later monitored deformation and stress data also verified the above calculation conclusion.

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