

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

Da Wei SUN, Liang ZHANG, Hui Qing YAO, Kang Ping WANG

Three Gorges University Key Laboratory of Geological Hazards on Three Gorges Reservoir Area, Ministry of Education, Yi'chang, Hubei 443002, China

Email: [daweisun@126.com](mailto:daweisun@126.com)

**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  $\nu = 0.167$ . The elastic modulus of concrete face slab and toe slab is:  $E = 31,500 \text{ MPa}$ , the elastic modulus of concrete retaining wall is  $E = 20,000 \text{ MPa}$ .



Figure 1. Photo of slope foundation

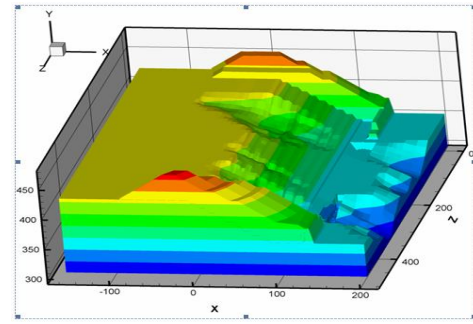


Figure 2. 3D rendered mesh of foundation

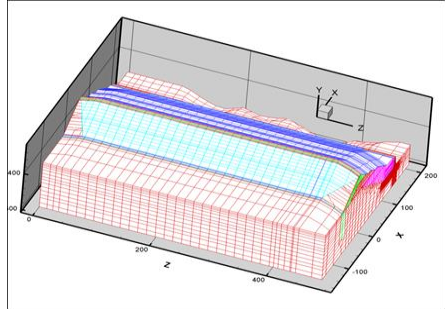


Figure 3. Mesh of main dam, retaining wall and foundation

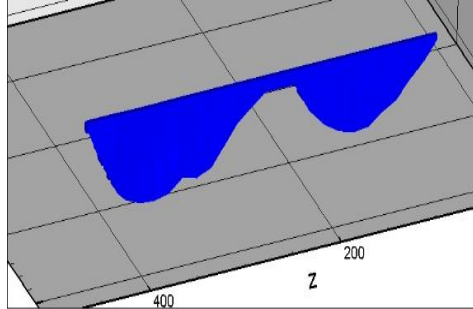


Figure 4. Rendered mesh of retaining wall

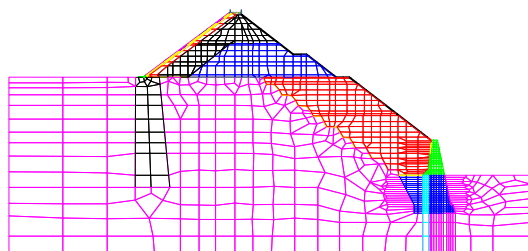


Figure 5. Material zone and construction process

#### 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:

$$\left. \begin{aligned} E_t &= \left[ 1 - R_f \frac{(1 - \sin \phi)(\sigma_1 - \sigma_3)}{2c \cos \phi + 2\sigma_3 \sin \phi} \right]^2 k P_a \left( \frac{\sigma_3}{P_a} \right)^n \\ B_t &= k_b P_a \left( \frac{\sigma_3}{P_a} \right)^m \end{aligned} \right\} \quad (1)$$

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):

$$E_{ur} = k_{ur} P_a \left( \frac{\sigma_3}{P_a} \right)^n \quad (2)$$

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

$$\phi = \phi_0 - \Delta\phi \lg \left( \frac{P}{P_a} \right) \quad (3)$$

The material parameters in equation (1) to (3), such as  $k$ ,  $k_b$ ,  $k_{ur}$ ,  $R_f$ ,  $c$ ,  $\phi_0$ ,  $m$  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.

Table 1 Parameters of Duncan-Chang E-B model of rockfill materials

Material Name	$\gamma_d$ (kN/m <sup>3</sup> )	$c$ (kPa)	$\Phi$ (°)	$\Phi_0$ (°)	$\Delta\Phi$ (°)	$K$	$n$	$R_f$	$K_b$	$m$	$K_{ur}$
Bedding layer	21.7	198	40.2	56.9	13.5	1080	0.48	0.75	250	0.35	2 K
Main rockfill Zone 1	21.7	156	40.2	53.1	8.5	715	0.34	0.86	270	0.28	2 K
Main rockfill Zone 2	21.7	154	42.1	55.1	8.9	800	0.44	0.86	450	0.42	2 K
Transition Zone	21.9	133	43.7	52.2	6.5	1090	0.47	0.73	250	0.37	2 K

### 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:

$$\begin{aligned} \tau_s &= \lambda_s \Delta u \\ \sigma_n &= \lambda_n \Delta v \end{aligned} \quad (4)$$

where  $\tau_s$  is shear stress and  $\sigma_n$  is normal stress.

Table 2 Parameter of Desai thin layer element model

$R_f$	$K_1$	$n$	Force	$K_y$	$\delta/$	$C (kPa)$
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:

$$\begin{Bmatrix} \tau_{yx} \\ \sigma_{yy} \\ \tau_{yz} \end{Bmatrix} = \begin{bmatrix} k_{yx} & 0 & 0 \\ 0 & k_{yy} & 0 \\ 0 & 0 & k_{yz} \end{bmatrix} \begin{Bmatrix} \delta_{yx} \\ \delta_{yy} \\ \delta_{yz} \end{Bmatrix} \quad (5)$$

$\tau_{yx}$ —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 22.0cm and the maximum horizontal downstream displacement is 10.3 cm.

Table 3 Maximum value of deformation of dam body (unit: 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

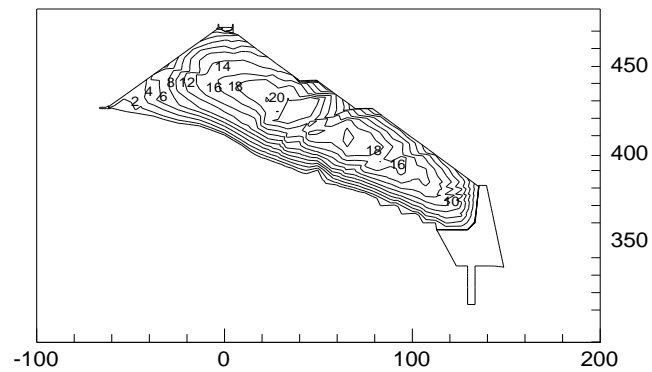


Figure 6. Vertical settlement at the completion of construction (Unit: cm)

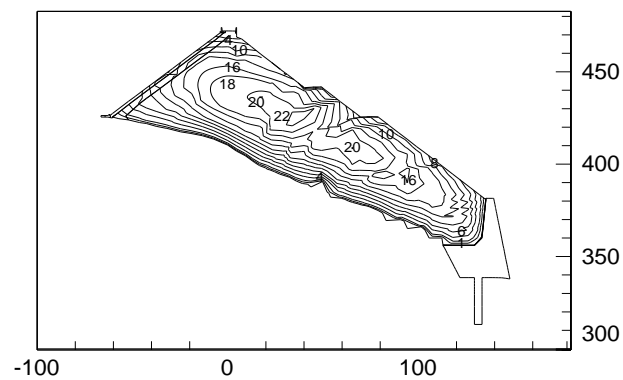


Figure 7. Vertical settlement after impoundment (Unit: cm)

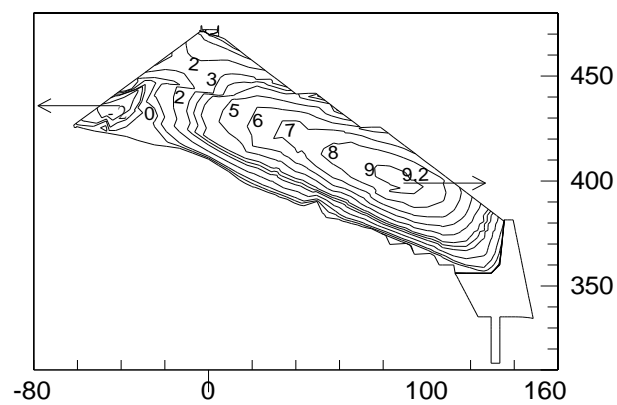


Figure 8. Horizontal displacement at the completion of construction (Unit: cm)

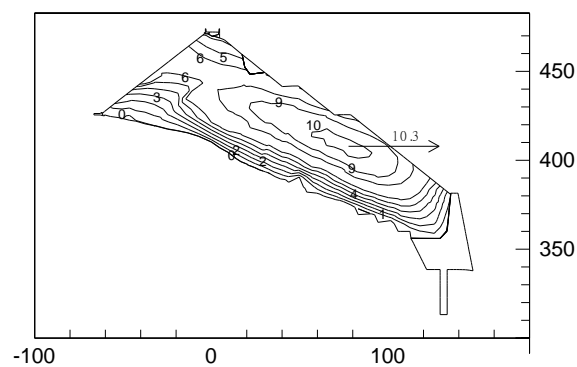


Figure 9. Horizontal displacement after impoundment (Unit: cm)

#### 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.

Table4 Maximum value of deformation of face slab after impoundment (unit:cm)

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

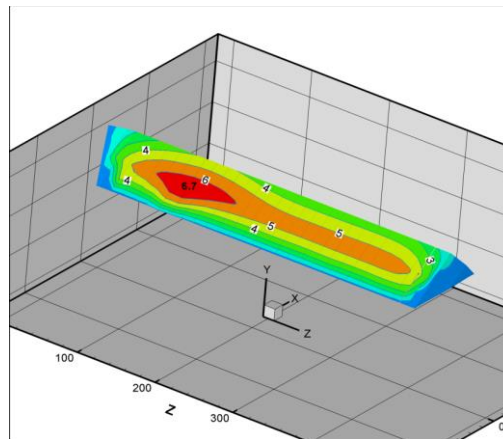


Figure 10. Face slab defection after impoundment (Unit: cm)

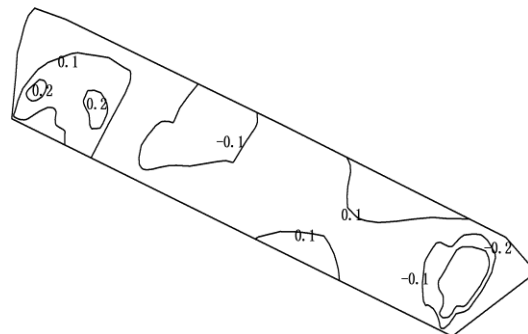


Figure 11. Face slab axial displacement after impoundment (Unit: cm)

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)

Deformation 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
perimetric 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.

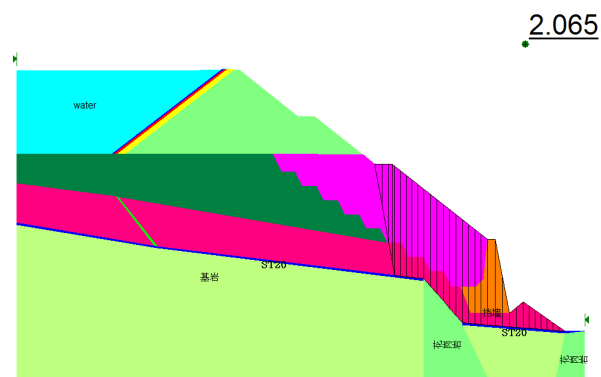


Figure 12. stability analysis result of retaining

## 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.

## Acknowledgements

This work was financially supported by National Natural Science Foundation of China (51179097) .

## References

- [1] Li Nenghui. The new technology of high concrete face rockfill dam, Beijing, China Water Conservancy and Hydropower Press, 2007.
- [2] Cao Keming, Wang Yisen, XU Jianjun, Liu Sihong. The concrete faced rockfill dam, Beijing, China Water Conservancy and Hydropower Press, 2008.
- [3] Duncan J. M & Chang C.Y. Nonlinear analysis of stress and strain in soil[J]. Journal SMFE, 1970, 96:1629-1653.
- [4] Desai C.S., Zaman M.M. Thin – layer element for interfaces and joints[J]. International Journal of Numerical and Analytical Methods in Geomechanics, 1984,8: 19-43.
- [5] ZHAO Kui-zhi, LI Guo-ying, MI Zhan-kuan. Design optimization for impervious system of Hangpingzui Rockfill Dam with concrete facing slab[J]. Hydro-science and Engineering,

- 2004, 6(2): 45–50. (in Chinese)
- [6] Sun Dawei. Study on stress and deformation behavior of high CFRD on deep overburden[D]. 2006, Ph.D. Thesis, Nanjing Hydraulic Research Institute. (in Chinese)
- [7] Sun Dawei, Li Neng Hui. The progress and Prospect of research on the key technology of concrete face rockfill dam on deep overburden layer[J]. The Journal of water power, 2005, 31 (8): 67-69.