03 Jun 1993, 4:30 pm - 5:30 pm

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Proceedings: Third International Conference on Case Histories in Geotechnical Engineering, St. Louis, Missouri, June 1-4, 1993, Paper No. 6.19

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SYNOPSIS: The monitoring of displacement is one of major measures to ensure the safety of an arch dam. And the back-analysis is a key link in the safety evaluation. This paper presents a case history of monitoring and back-analysis of displacement in Dongjiang Arch Dam, China. The elasticity modulus of dam foundation were determined by back-analysis of displacement for lower water level in the reservoir. The prediction of displacement of dam was compared with the results of monitoring. The suggested procedure of 3D finite element computation coupling solid and temperature stresses can be used for other types of rock engineering.

1. INTRODUCTION

Dongjian Hydro-electric Power Station is located in the upper reach of Leishui River, a tributary of Xiangjiang River in Hunan Province. It is a concrete double arch dam with 157 m of maximum dam height, 35 m of the thickness of dam bottom and 7 m of the width of the dam top. The dam foundation is composed of fresh intact granite which is perfectly suitable for arch dam. In construction, the dam foundation has been treated by grouting consolidation. The faults and major fractures have been specially treated. The deep-hole watertight curtains have been put in the dam foundation, and the drinage system has been arranged behind the curtains and at two banks.

For the safety of Dongjian dam and for the control of the deformation of the arch dam and its foundation a monitoring system was set up in dam building and the observation was carried on during water impounding. In order to estimate and monitor the working situation of the dam,to examine the rationality of the design, and to improve the design procedure, a method of back-analysis for determing the elasticity modulus in the heterogenous dam foundation was developed. The result of back-analysis was used for prediction of deformation of the dam and checked by the data obtained in the further monitoring.

2.ENGINEERING AND GEOLOGICAL CONDITIONS

2.1 Geomorphological Features

The mountain slopes along the two symmetric banks in the dam site are 500 m high. The valley shows V-shape and the bank slopes have the angles of 45°-50°. The ratio between the width and height of the valley is 2:1, and the bed rock are fully exposed on the outcrops. In the mean water level, the width of the water is 20-40 m, and the water depth is 1-3 m. The depth of sand and gravel layer in the river bed is 3-5 m.

2.2 Geological Conditions

The dam foundation and abutments are composed of granite of Yanshanian orogeny which can be divided into three intrusion stages.

Distributed below 260-290 m above the sea level, the plutonic granite in the first stage can be divided into the marginal fine granite (γ_A^1), the transitional middle fine to middle porphyritic granite (γ_A^2) and the central coarse porphyritic granite (γ_A^3). The dark dykes such as lamprophyre (x_A) are developed in the granite of first stage filling in the NEE-striking fractures. The plutonic granite in the second stage is distributed below 300-350 m above the sea level and composed of middle fine granite (γ_B^1) and middle coarse granite (γ_B^2). The later dykes (γ_{2B}), such as granite-pegmatite and granite-aplite, are distributed striking NEE and NNW. The hypabyssal granite-porphyry ($\gamma_{\pi c}$) in the third stage is undivided dykes. It intersected into the granite and surrounding sedimentary rocks along NEE direction.

The area of dam site belongs geotectonically to the Neocathaysian tectonic system. A NNW-orientation and flat dipping flow structure is developed in the granite. There are two sets of cross and longitutional joints striking NNW and NEE.

Faults F_2 and F_3 are located in the dam site at 10 and 100 m from the upper edge of the dam base striking N60-70E and dipping SE with dipping angle of 70°- 80°. The crushed zone of faults is 0.2-1.5 m wide and the fractured zone is 1.5-2.0 wide.

Fractures K_1-K_{11} are located in the dam foundation and the downstream area, and have a striking of N60-75E, dipping of SE with dipping angle of 70°-80°.

After excavation the dam was based on slightly weathered or fresh granite.

The depth of underground water table is 72 m in the left bank and 48 m in the right bank. The depth of the top layer with a water absorbtion less than 1.0 lugeon is 8-10 m in the river bed 15-53 m in the left bank and 10-50 m in the right bank.

The engineering geological map of the dam site in Dongjiang Hydropower station is shown in Fig.1

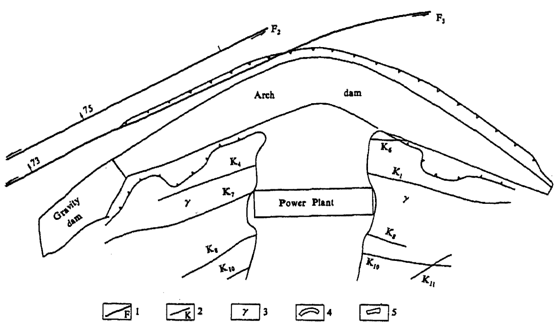

Fig.1 The Engineering Geological Map of the Dam Site in Dongjiang Hydropower Station

1. Fault; 2. Fracture; 3. Granite; 4. Arch dam; 5. Power plant

2.3 FOUNDATION TREATMENT

The Dongjiang dam site is of geomorphological and geological conditions suitable for construction of an double arch dam. The dam foundation is composed of unweathered and intact granite. The arch dam has a basement of 35 m width and the thickness-height ratio is equal to 0.223. The basement excavation is of high quality with 3D prefissuring blasting. Compared with the original design line, the average extra excavation is only 0.13 m. According to the results of cross hole measurement the average velocity of sonic wave is up to 5480 m/s. For sake of the stability the dam foundation and abutments were treated by consolidation grouting, and special grouting was made for strengthening of the faults and fractures. The deep-hole water-tight curtain has been put in dam foundation with high pressure grouting. After injection the permeability is less than 0.5 lugeon. A perfect dringe system has been put behind the grouting curtain and in the abutments in the two banks.

3. PRINCIPAL MONITORING SYSTEM

The monitoring system was designed for observing the displacement and tilting of dam foundation and dam structure.

The normal-reverse penduloms were set up for monitoring. It is a reliable instrument and can yield perfect information. Since it is buried deeply in the rock foundation, the pendulom line has a relatively stable environment. The temperature variation is limited and outer disturbance can be avoided.

The monitoring stations of the normal and reverse penduloms lines are shown in Fig.2.

Using the normal-reverse penduloms the displacement of the crown of dam structure can be measured. The measured displacement is in horizontal direction. The back-analysis presented in this paper is based on the results obtained with the normal-reverse pendulom method.

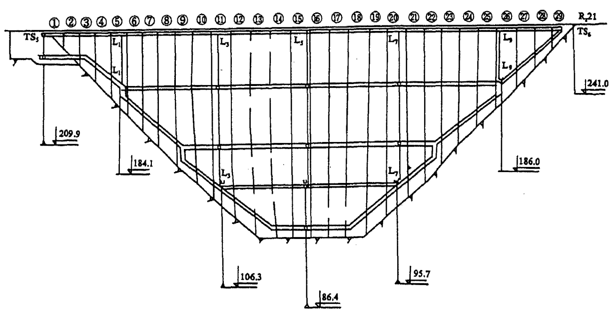

Fig.2 Location of Stations of Pendulom Lines in Dam Structure

The reservoir impounding began in July 1986 and it reached in level of 258.2 m in June 19,1989. The measured values of horiyontal displacement are shown in Table 1.

Table 1

Elevation of measuring point (m)	Arch crown N.15 (mm)	Right block N.11 (mm)	Left block N.20 (mm)	Right block N.5 (mm)	Left block N.26 (mm)
145	1.35				
175	4.89	1.99	0.02		
205	7.83	4.34	3.00		
250	5.92	3.82	-0.91	-1.21	-1.99

4. BACK-ANALYSIS METHOD AND RESULTS

The parametres of mechanical properties of rock foundation were determined by laboratory and field tests. However, the mechanical behavior of rock foundation under the dam loading must be different from those obtained by tests for design. In order to achieve the realistic properties of rock foundation the back-analysis was conducted using 3D finite element program with joint element. The computational model of the arch dam and its foundation is shown in Fig.3.

The first step is to estimate the difference between the mechanical parametres used in designal computation and the real values. This can be achieved by comparing the measured and computed displacements. From the Fig.4 it can be seen that the computed displacement is much larger than measured one. This means that the elasticity modulus of rock foundation may be much higher than that to be expected during site investigation. This phenomenon is widly reported in literature.

In order to obtain the values of elasticity modulus which can reflect the foundation behavior under dam loading an optimal back-analysis procudure has been developed by the authors. The new methods can be used for determining the elasticity modulus of heterogeneous rock foundation

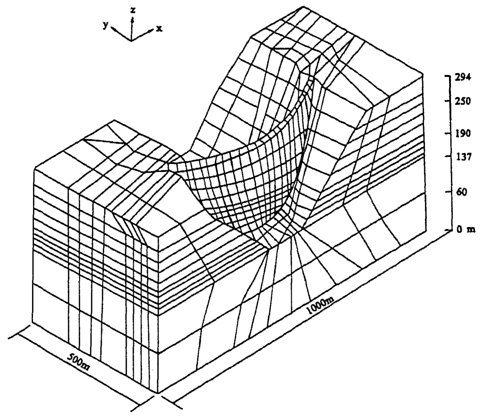

Fig.3 The Computational Model of Dongjian Arch Dam

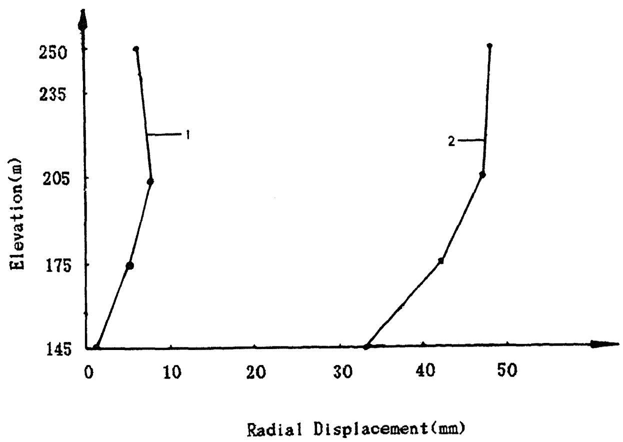

Fig. 4 The Measured And Computed Values of Displacement in Montoring Station No.15. 1. Measured Values; 2. Computed Values

with several relatively uniform areas.

Suppose, the design parameters are taken as series of modulus in n areas:

$$\{E\} = \{E_1, E_2, \dots E_n\} \tag{1}$$

According to the principle of the least square, the object function can be expressed as following.

$$J = \sum_{j=1}^{m} (u_j - u_j^m)^2 \omega_j \tag{2}$$

where u_j, u_j^m are the computed and measured displacements respectively in point j; ω is the weight factor.

The objective of back-analysis is to estimate the optimal series of modulus $\{E\}$. Under the conditions of constraints $E_j > 0$, the least value of object function is taken in the back-analysis.

Suppose the elasticity modulus of i area is E_i, the finite element formulation can be written as

$$\sum_{i=1}^{n} E_i \left[K_i\right]\{u\} = \{F\} \tag{3}$$

Suppose $E_i = (1/\alpha_i) E_i^0$ and E_i^0 is an assumed initial value of modulus of i area, we have

$$\sum_{i=1}^{n} (1/\alpha_i)\, E_i^0 \left[K_i\right]\{u\} = \{F\} \tag{4}$$

and the relationship between $\{u\}$ and $\{\alpha\}$ is established. Finally, we could obtain

$$J = \sum_{j=1}^{m} \left[(u_j^0 - u_j^m) + \sum_{i=1}^{n} \frac{\partial\{u\}}{\partial E_i} (E_i - E_i^0) \right]^2 \omega_j = J (\alpha_1, \alpha_2, \dots \alpha_n) \tag{5}$$

An optimal program of iteration was compiled to determine series $\{\alpha\}$

For obtaining the optimal modulus in Dongjiang dam the water level, temperature and measured displacements on June 19,1989 are taken into back-analysis computation.

The series of modulus is divided into 3 areas, i.e. E_1 for dam body, E_2 for rock foundation upperstream from fault F_3 for rock foundation downstream from F_3.

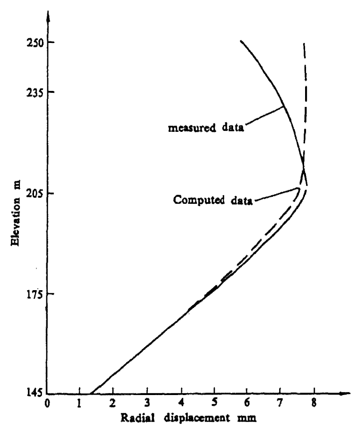

Fig.5 Comparison of Measured and Computed Displacements for the dam block N.15

The results of back-analysis are shown in Table 2. The optimal modulus are higher than that used in designal computation.

5. VARIFICATION OF BACK-ANALYSIS AND PREDICTION OF DISPLACEMENTS

In order to varify the reliability of the results of the back-analysis, we used the obtained values of elasticity mudulus into finite element computation. The computed displacements become very close to that measured. The results for crown of dam block N.15 are shown in Table 3 and Fig.5.

Table 2. The Results of Back-analysis for Elasticity Modulus of The Dam Body And The Bed Rock

	Elasticity Modulus from Back-analysis (Mpa)	Design Values of Elasticity Modulus (Mpa)
Dam Body	$2X10^4$	$2X10^4$
Upstream from F_3	$2X10^4$	$3.2534X10^4$
Downstream from F_3	$2.1X10^4$	$3.2534X10^4$

Table 3. The Comparison between The Computed Displacement And The Measured Displacement (mm)

Elevation(m)	145	175	205	250
Computed Displacement	1.35	4.89	7.83	5.92
Measured Displacement	1.36	4.91	7.68	7.70

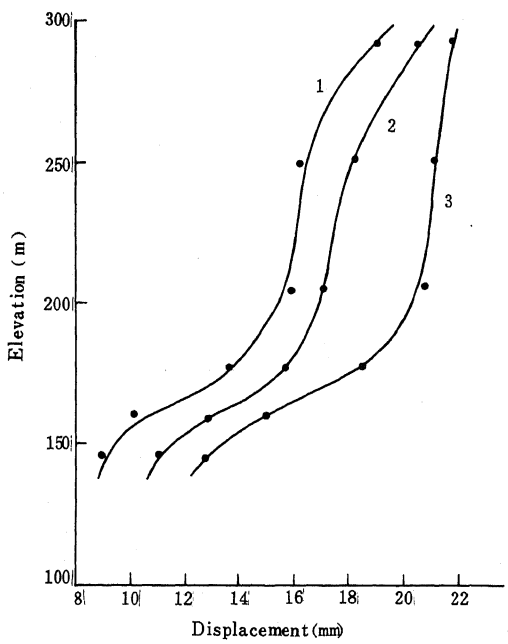

Fig. 6. Predicted Displacements of Dam Body No. 15 during Temperature Increasing Process. 1. Water Level 265 m; 2. Water Level 275 m; 3. Water Level 285 m.

After readjustment of the computational parameters the model can be used for prediction of the displacements of dam blocks during further reservoir impounding. In this prediction the processes of temperature increasing and decreasing in different season are to be considered. The prediction was made for the water level in reservoir at elevation of 265 m, 275 m and 285 m (normal level of reservoir), as shown in the Fig. 6 and Fig. 7. For water level in between the 265 m, 275 m and 285 m the predicted values of displacement can be obtained by interpolation.
Here, the authors might as well point out that two techniques, namely, the standard pattern method (Yang Zhifa and Liu Zhuhua, 1982) and the grey system (Deng Julong, 1987) could be used for the back-analysis of a dam. The former could help us to save a lot of CPU time of

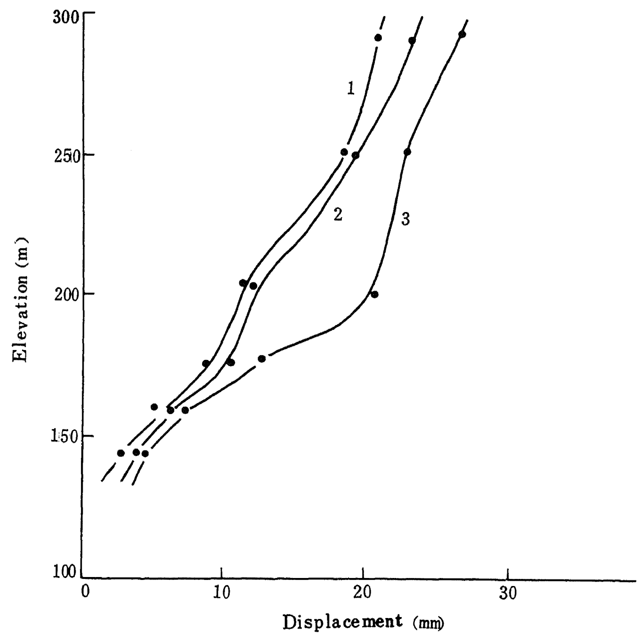

Fig. 7. Predicted Displacements of Dam Body No.15 during Temperature Decreasing Process. 1. Water Level 265 m; 2. Water Level 275 m; 3. Water Level 285 m.

Computation in three dimensions which is necessary for the back-analysis of a dam; The latter is more useful to predict the water level in reservoir and temperature of the water and the air in accordance with the data measured before the prediction. Because space forbids, their principles and methods will be omitted.

6. CONCLUSION

The application of the back-analysis to Dongjian arch dam shows that the method to predict the displacements of dam body and its bed rock is feasible. The authors believe that the method could be used for other dams and will be improving in its application.

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