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A Study on the Bearing Capacity of Cement-Sand-Gravel Dam Foundation

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Abstract: Hydraulic model test is used to explore the stress distribution and bearing capacity of cement-sand-gravel dam foundation. Through stepwise and multi-level loading of the dam body, the stress distribution of the dam body under hydraulic load is obtained along with the stress distribution under the dead weight of the dam body. Experiment shows that under the action of dead weight, both the dam body and the foundation are subjected to compression, with higher compressive stress in the middle and lower stress on the two sides. When the upstream hydraulic load acts on the dam body, there is a change of stress distribution pattern of the dam body. The largest stress occurs in the middle and downstream part of the dam foundation. The radial displacement of the dam body changes to displacement in downstream direction. The displacement of the upper part of the dam body is higher than that of the lower part of the dam body, with the maximum displacement occurring in the middle of the dam.

Keywords: *Cement-sand-gravel dam, model test, stress analysis, dead weight of the dam body*

1. Introduction

Cement-sand-gravel dam is a new type of dam with trapezoidal cross-section that resembles the cross-section of an earth-rock dam, while the material strength lies intermediate between that of concrete dam and earth-rock dam. As to the stability of the dam foundation, the cement-sand-gravel dam inherits the advantages of the earth-rock dam. As compared with conventional gravity dam, the cement-sand-gravel dam body is a triangle with vertical upstream face, which has higher anti-slide stability and overturning stability. The dam body is composed of cement, sand and gravel, which are rigid materials, while dam foundation is largely made of non-rock materials. Therefore, this type of dam is easily affected by foundation settlement, plastic deformation, and shear failure or even cracking under the action of dead weight. Bearing capacity of dam foundation is crucial for dam stability. For cement-sand-gravel dam, the effect of rock mass of the foundation on the dam body should be fully considered in optimizing the dam structure.

In engineering practice, the common methods of stress analysis fall into the following categories: theoretical analysis based on material mechanics, finite element method based on elastic theory, and testing of linear elastic stress model. Methods of stability analysis include theoretical calculation based on rigid body equilibrium limit method, finite element method based on elastic theory and failure test of elastoplastic model. Model test involves the modeling of the actual structure according to certain principles. Besides working conditions of the structures and its foundation, the model also considers various load combinations (normal and abnormal) and complex boundary conditions. Using the stress, strain and displacement data observed from model test, the mechanical characteristics of the actual structure are derived based on structural similarity.

Model test is used in this paper for simulating the effect of the pouring process on the cement-sand-gravel dam foundation and dam body. The stress and strain distribution of the dam body during normal operation is obtained by simulation. On this basis, the method and standard for controlling material strength are determined. The findings of this study provide reference for assessment of bearing capacity of cement-sand-gravel dam foundation.

2. An overview of the project and model design

2.1 An overview of the project

Shoukoupu Reservoir is located in the upstream of Heshui River in Yanggao County, Datong City, Shanxi Province. It is the first permanent cement-sand-gravel dam built in China. The maximum dam height is 60.6m, the inclination of the upstream and downstream slope is 1:0.5, and the cementing material is 50kg/m3 cement and 40kg/m3 fly ash. The bulk density of the dam body is 23.2kN/m3, E and being 4Gpa and 0.20, respectively. The bulk density of the dam foundation is 20.2kN/m3, E and being 7Gpa and 0.24, respectively.

2.2 Model test

Similarity coefficients and indicators for model test are first determined: geometric similarity constant

CL=100, bulk density similarity constant Cγ=1.25, Poisson's ratio similarity constant Cε=1.0, stress similarity constant Cσ=Cγ · CL=125, displacement similarity constant Cδ=CL=100, load similarity constant CF=Cγ · CL3=1.25×1003, modulus of deformation similarity constant CE=Cσ=125, friction coefficient similarity constant Cf=1, and cohesion similarity constant Cc=Cσ=125.

Based on the above similarity constants and the actual conditions of the project, the dam height is determined as H=60.6cm. During simulation, the depth of the foundation is 50cm, the length of the upstream part of the dam 30cm and the length of the downstream part of the dam 150cm. A coordinate system is constructed using the heel of the upstream part of the dam as the origin.

2.3 Measurements and loading

Strain and displacement of the dam are measured in the model. The strain is measured with resistance strain gauge, with 9 measuring points arranged at 3cm below the foundation face and 9 measuring points at the base of the dam body. Meanwhile, 5 measuring points are arranged in the middle and lower part of the dam body and at 23cm from the foundation face, respectively. Strain gauges are installed at the same positions on the other side of the dam body, as shown in Fig. 1.

The displacement of the dam body is measured with displacement digital display. Horizontal and vertical displacement sensors are installed to the top of the upstream face of the dam body, turning point of the downstream face, 1/2 height of dam body, toe of dam and foundation. The positions of the strain gauges and displacement sensors are shown in Fig. 1.

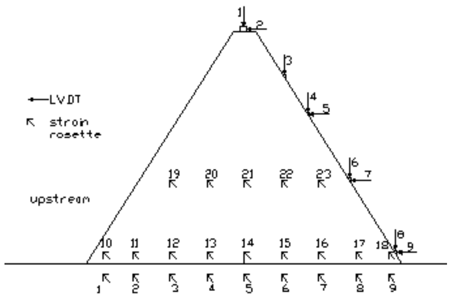

Fig.1 *Positions of the strain gauges and displacement sensors*

Normal storage level in the upstream is taken as the hydraulic pressure. Loading is simulated using a hydraulic jack. Bulk density of the dam body materials is considered equal to that of actual materials. Temperature load is most detrimental to the stability of the dam abutment. Since it is difficult to simulate the temperature field in model test, temperature load is approximately simulated as temperature load equivalent.

2.4 Steps of model test

The dam body is divided into four layers, and the height of each layer is 15m. The concrete layer of the dam body is loaded stepwise to the dam foundation. The effect of loading on the dam body and dam foundation is monitored by using strain gauges. Thus the working conditions of the dam body and dam foundation during the pouring process are acquired.

After the pouring is finished in the dam top, the dam body is cemented by high polymer materials. Hydraulic load from the upstream is simulated using a hydraulic jack. The stress and strain distributions of the dam body during pouring and under normal operation are obtained.

3. Material simulation

3.1 Material performance analysis

The strength of cement sand and gravel (CSG) is affected by water-to-binder ratio, cement content, fly ash content, sand percentage and clay content. Water-to-binder ratio is the key parameter in the design of mixing proportion and determines the performance of over lean cemented material. According to Sun et al., the optimal water-to-cement ratio of the over lean cemented material ranges from 0.8 to 1.2. Sand percentage is another key parameter in the design of mixing proportion of over lean cemented material, and the optimal value is 0.2. By model test, the curve of water-to-cement ratio vs. elastic modulus of CSG is plotted, as shown in Fig. 2.

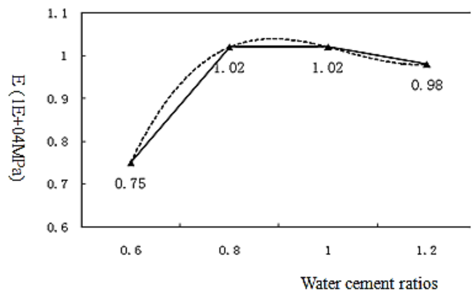

Fig. 2 *Curve of water-to-cement ratio vs. elastic modulus of CSG*

3.2 Material test

The model of CSG material is prepared using barite powder and model sand as aggregates and plaster and high polymer materials as cementing agent. Through mixing proportion test, the model of CSG material similar to the actual dam is constructed and the modulus of deformation is tested. The elastic modulus of the model material is 46.02MPa, which meets the similarity requirement (Fig. 3).

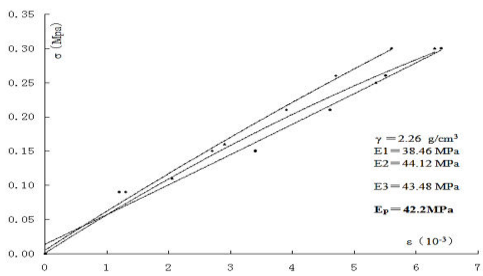

Fig. 3 *Dam material test*

4. Result of model test

Failure test is carried out using overloading method. After the loading of dead weight, multi-level overloading of hydraulic pressure from upstream is performed until failure and instability of the dam body and dam foundation. The deformation and failure under each step of loading are observed. The following results are obtained:

(1) Variation of distribution of displacement at 5 typical displacement measuring points in the downstream face of the dam body;

(2) Variation of distribution of strain at 3 typical strain measuring points in the downstream face of the dam body, which is converted to stress using formula (1) and (2).:

$$\left.\begin{aligned} \sigma_x &= \frac{E_m}{1-\mu^2} C_l \cdot C_f (\varepsilon_x + \mu\varepsilon_y) \\ \sigma_y &= \frac{E_m}{1-\mu^2} C_l \cdot C_f (\varepsilon_y + \mu\varepsilon_x) \\ \tau_{xy} &= \frac{E_m}{2(1+\mu)} C_l \cdot C_f \left[2\varepsilon_{xy} - (\varepsilon_x + \varepsilon_y)\right] \end{aligned}\right\} \quad (1)$$

Where, σ_x, σ_y and τ_{xy} are the horizontal and vertical normal stress and shear stress of the actual dam, respectively.

E_m and μ are elastic modulus and Poisson's ratio of the model material, respectively.

C_f and C_1 are density and geometric similarity constant, respectively ($C_f = C_\gamma$).

ε_x, ε_y and ε_{xy} are the measured strain values in horizontal and vertical direction and at 45° angle, respectively.

With the obtaining of, and, the principle stress is given as follows:

$$\left.\begin{aligned} \sigma_{1,2} &= \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2} \\ tg\,2\alpha &= \frac{2\tau_{xy}}{\sigma_x - \sigma_y} \end{aligned}\right\} \quad (2)$$

Where, the higher principle stress is the first principle stress.

4.1 Stress distribution of dam body and dam foundation during pouring process

The dam is poured layer by layer at a height interval of 15m. The pouring of the third layer is simulated, as shown in Fig. 4.

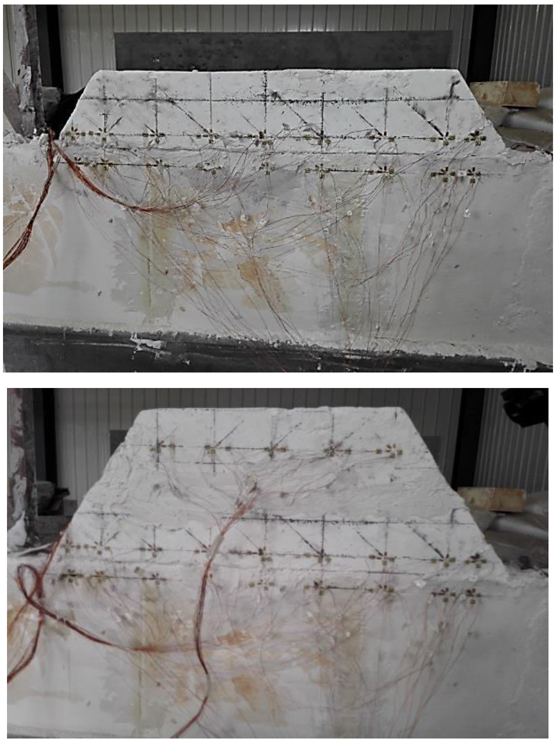

Fig. 4 *Simulation of the pouring process*

During the simulation of multi-layer pouring, the stress and strain values are measured at the dam body and dam foundation using strain gauges. The stress changes of dam foundation and dam base in each pouring are analyzed using Hooke's law, as shown in Table 1-2.

Table 1 *Stress changes in each pouring*

No.	1	2	3	4	5	6	7	8	9
σ1 during pouring of first layer (Mpa)	-0.06	0.28	0.31	0.56	0.38	0.46	0.43	0.36	-0.09
σ1 during pouring of second layer (Mpa)	-0.03	0.29	0.35	0.56	0.53	0.50	0.51	0.39	-0.09
σ1 during pouring of third layer (Mpa)	-0.06	0.30	0.50	0.80	0.70	0.60	0.69	0.46	-0.21
σ1 during pouring of forth layer (Mpa)	-0.08	0.46	0.61	0.81	0.71	0.64	0.70	0.50	-0.29

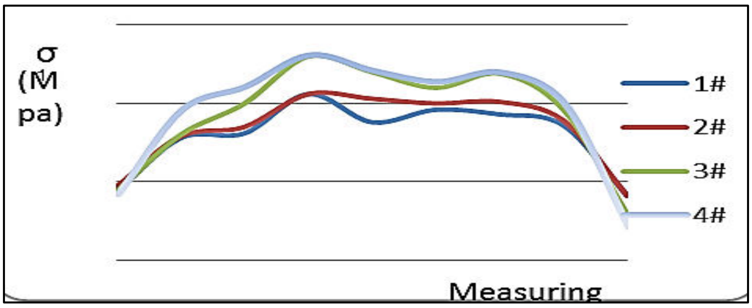

Fig. 5 *Stress changes of dam foundation in pouring of each layer*

***Table 2** Stress changes of dam base in each pouring*

No.	10	11	12	13	14	15	16	17	18
σ1 during pouring of second layer (Mpa)	0.06	0.18	0.24	0.31	0.33	0.30	0.34	0.16	0.06
σ1 during pouring of third layer (Mpa)	0.16	0.24	0.36	0.38	0.46	0.53	0.29	0.19	0.11
σ1 during pouring of forth layer (Mpa)	0.20	0.34	0.46	0.56	0.58	0.58	0.56	0.31	0.13

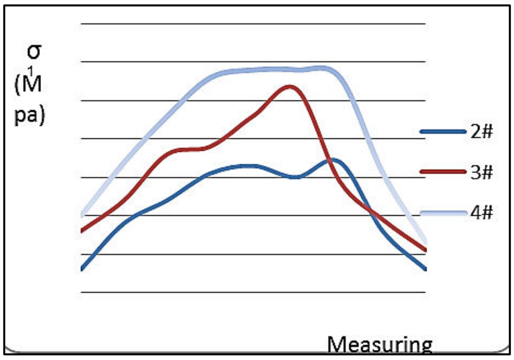

***Fig. 6** Stress changes of dam base in pouring of each layer*

Generally both the dam body and dam foundation are subjected to compressive stress, and only the toe and heel of the dam are under tensile stress. At the same elevation, the compressive stress of the dam body increases from the heel of dam to the middle of the dam body and from toe of dam to the middle of the dam body. The compressive stress is the largest in the middle of the dam body and shows uniform distribution. At different elevations, the compressive stress varies significantly with dead weight of the dam body, with the maximum compressive stress occurring in the middle of the dam foundation.

As shown in Table 1-2, the principle stress of the dam body during pouring is smaller than the compressive strength of the dam body. However, non-uniformity of stress distribution in the dam foundation will lead to uneven settlement of dam foundation, especially for soft foundation. Because the tensile strength of the CSG material is low, uneven settlement of dam foundation may cause dislocation and rupture of the dam body, resulting in leakage and affecting dam stability.

4.2 Simulation of normal working conditions of the dam

4.2.1 Stress distribution

The dam is cemented by high polymer materials and the hydraulic pressure from the upstream is simulated using a hydraulic jack, as shown in Fig. 7.The normal working conditions of the dam are simulated and the stress distribution of dam body is obtained. The superimposed stress distribution of the dam body is shown in Table 3.

***Fig. 7** Whole dam model*

***Table 3** Stress distribution of the dam body*

Dam foundation (serial No.)	1	2	3	4	5	6	7	8	9
σ1 (MPa)	0.13	0.41	0.56	0.76	1.36	1.15	1.14	0.70	0.50
Dam base (serial No.)	10	11	12	13	14	15	16	17	18
σ1(MPa)	0.04	0.40	0.54	0.69	0.95	0.86	1.03	0.95	0.99
Middle of the dam (serial No.)	19	20	21	22	23				
σ1 (MPa)	0.08	0.43	0.80	0.30	0.38				

Both the dam body and the dam foundation are subjected to compression. Under dead weight of dam body and hydraulic pressure, the maximum compressive stress is located in the middle and downstream part of the dam at the same elevation. At different elevation, the compressive stress varies significantly with the dead weight of the dam body and hydraulic pressure. The maximum compressive stress occurs in the middle of the dam foundation.

As hydraulic pressure from the upstream acts on the dam body, the stress distribution is jointly influenced by hydraulic pressure and dead weight of the dam body. As a result, the stress distribution of the dam body varies, and the maximum stress occurs in the middle and downstream part of the dam. The stress distribution is still uneven, leading to non-uniformity of dam foundation settlement.

4.2.2 Displacement distribution

Nine displacement sensors are installed at 4 typical elevations in the downstream part of the dam body, for measuring radial and vertical displacement of the dam body. The positions of the displacement sensors are shown in Fig. 1, and the displacement values at each point are given in Table 4. Displacement is expressed in the unit of mm. Radial displacement in the downstream direction is considered positive, and the vertical displacement in the upstream direction is considered positive.

Table 4 *Displacement distribution of the dam body*

NO	1	2	3	4	5	7	8	9
Displacement (mm)	-3	3	-2	-2	5	3	-2	4

Radial displacement occurs in the downstream direction, and the upper part of the dam has larger displacement than the lower part, with the maximum value occurring in the middle of the dam. Under normal conditions, the radial displacement is 5mm. The vertical displacement of the dam is generally small and in the downstream direction. The maximum displacement is found at the dam top and the value is 3mm under normal conditions.

5 Conclusions

As indicated by the multi-layer loading model, both the dam body and the dam foundation are subjected to compression due to the dead weight of dam body. Only the heel and toe of the dam are subjected to tensile stress, with the maximum compressive stress occurring in the middle of the dam body. The principle stress of the dam body is smaller than the compressive strength of the dam body and therefore the dam body is little affected. However, non-uniformity of stress distribution in the dam foundation will lead to uneven settlement of the dam foundation, especially for soft foundation. Under operating conditions, both the dam body and dam foundation are subjected to compressive stress. The stress distribution of the dam body changes dramatically due to dead weight of dam body and hydraulic pressure. The maximum compressive stress is found in the middle and downstream part of the dam body and its distribution is still uneven, leading to non-uniformity of dam foundation settlement. Because of low tensile strength of CSG material, non-uniformity of dam foundation settlement may cause dislocation and rupture of the dam body and hence leakage and instability of the dam body. The shifting of the region of maximum principle stress is accompanied by the shifting of the failure region in the dam foundation. With the formation of sliding channels, the dam stability is impaired.

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