Mechanism of cracks and rehabilitation schemes of some Arch Dam

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Abstract: Some Arch Dam has been in operation for more than 20 years, and many cracks have occurred in the dam body. After several times patches processing, the cracks still have the tendency of development, which have seriously affected the overall safety of the dam. In order to analyze the cracking mechanism and to study the feasibility of rehabilitation schemes, the stress and the deformation laws of the dam body and foundation under different loads are analyzed by use of 3D FEM. The active status of the arch dam under the design condition is simulated by the actual increase load process. In addition, the mechanism of cracks is analyzed, and a reinforcement scheme is proposed, in which the upstream surface spurts the thermal insulation materials and the downriver surface hangs spurts the steel textile fiber concrete. In order to determine the rationality of the rehabilitation scheme, 3D temperature fields of the dam are calculated, which provides the loads for the 3D stress field analysis. Then the stress and the deformation laws of the dam body under different operating modes are calculated, with the 3D finite element non-linear simulation method, during which the actual load increasing process and implementation process of the reinforcement scheme is simulated. With the above computed results, the rationality and the feasibility of the dam reinforcement scheme is evaluated. The dam safety monitoring data and the dam quality examination results demonstrate that the proposed rehabilitation scheme is effective.

Key words: crack; rehabilitation scheme, simulation analysis, Arch Dam

1 Introduction

The Reservoir is located on Some River in Yansi District of Huangshan City in Anhui Province, about 50 km away from Huangshan City. It is a multipurpose project for flood prevention, irrigation and power generation. The reservoir has a total storage capacity of $8\,400\times10^4\,m^3$, and the catchment area upstream the dam site is 297 km^2. It belongs to the middle-sized third class projects. The check water level with the return period of 500 years is 210.60 m, the design water level is 208.80 m, the normal water level is 201.00 m, and the dead water level is 183.00 m. The diversion dam is concrete double Arch Dam with variable center and radius as well as uniform thickness, with the dam crest elevation of 211.00 m, foundation elevation of 157.00 m, the maximum dam height of 54.0 m; the dam crest thickness of 2.5 m, the dam bottom thickness of 12.5 m, the thickness-height ratio of 0.23; the dam arch is 216.15 m in length, the dam crest arch is 168.2 m in length, the ratio of arch height is 4.0, the ratio of chord height is 3.1. The dam is divided into 16 blocks along the dam axis, and each block is about 12 m in width.

The Arch Dam started to be concreted in Jan. 1973 and concrete construction was completed in 1976. The repeated grouting of transverse joints was finished in March 1978. Thus the Arch Dam became an integral structure and was of impoundment and operation conditions. However, the whole project was not completed on schedule owing to the change of roads within the reservoir area. In order to ensure road traffic, the reservoir was not impounded for long time. In summer of 1978, the reservoir area witnessed long-term arid climate with high temperature, and the reservoir was in an empty state so that the dam body was under the long-term condition of empty reservoir storage + self-weight + temperature rising loads. Furthermore, the Arch Dam was much thinner, curvature of arch ring was much larger, the temperature loads resulted in upward displacement of the Arch Dam, and much larger tensile stresses were caused near the arch abutment of downstream dam face[1]. In winter of 1978, 9 and 3 cracks occurred on the downstream dam faces of the left and right banks, respectively, and in 1986 grouting treatment was performed. Distribution of cracks is shown in Fig. 1. Crack Nos. 1~20 occurred during 1979~1986, among which, 12 cracks were caused in the downstream in winter of 1978; the cracks without number were developed during 1986~2001. Bleeding phenomenon of water and dissociative calcium occurred at the cracks. These cracks not only had an effect on dam view and leakage, but also on dam strength and safety. It is necessary to analyze their causes for generation and development. And on such a basis, crack rehabilitation schemes are to be studied.

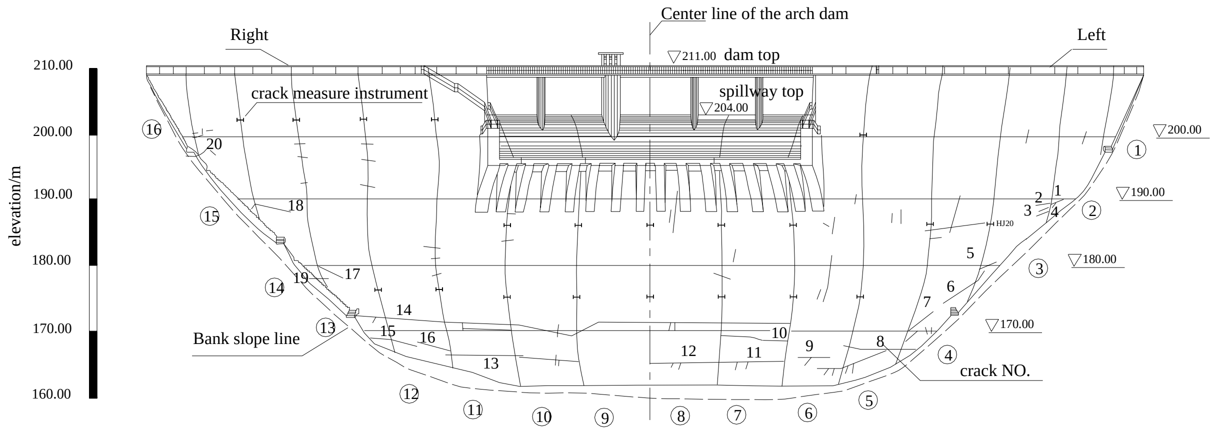

Fig. 1 Positions of cracks of downstream surface of the Arch Dam

2 Analysis of crack formation causes

2.1 Generation and development of cracks

When the cracks occurred, relative departments paid much attention. On the one hand, they organized certain unit to investigate and study the characteristics of cracks; on the other hand, they organized certain unit to study rehabilitation measures for cracks. Through investigation, from May 7 to Aug. 26, 1978, cracks occurred between the elevation of 195.00 m of No. 2 block and that of 165.00 m of No. 6 block of the left bank in the downstream, and they were basically parallel to the direction of slopes. The total length was about 80 m, and the width was up to 1.0 mm; the crack between the No. 12 block (elevation: 175.00 m) and No. 14 block (elevation: 1765.30 m) in the right bank extended 29.35 m along the horizontal structures at the elevation of 175.00 m. At the beginning of 1979, the cracks were rehabilitationed by use of epoxy resin, and in October, the cracks continued to open and extend towards both ends. In Dec. 1979, Nanjing Hydraulic Research Institute detected cracks near the arch abutment at the elevation of 184.0 0 m of the left bank in the downstream of dam by use of ultrasonic waves. The depth of cracks was larger than 2.3 m, the thickness of dam is 6.9 m. Because the cracks were not rehabilitationed in time, during 1979～Sept. 1986, 20 cracks occurred, and the total length was up to 260.8 m. At the intersection between the crack and horizontal joints of construction, the dam surface was wet and leakaged, and during the high water level, some cracks would give off water fog. In winter of 1986, 19 cracks were grouted by use of epoxy resin. After 331.2 L epoxy resin was grouted, the cracks did not leakage. By detection of ultrasonic waves, the wave amplitude of most cracks increased with large extent, and that of some cracks was close to that of seamless concrete[2].

After the grouting, the dam was in a state of normal operation. From the observed data during 1986～1994, the width of the cracks at the left bank of the downstream dam face had a tendency of increase. However, no new cracks were found, and the grouted cracks did not become larger. After 1996, new cracks continuously occurred in the downstream dam face, and the leakage points increased. Till the end of 2001, over 40 points were discovered, and white separated compounds were accompanied. Some intersections between the cracks and horizontal joints leakaged, and the seepage section was long, resulting in new cracks. Inspection on Dec. 14, 2001 shows that 6 horizontal or oblique cracks occurred at No. 6, No. 8, No. 10 and No. 11 blocks, and the total length was 28.1 m. Through the detections by use of ultrasonic waves respectively by Nanjing Hydraulic Research In statute and Anhui Provincial Hydraulic Research Institute in 1979 and 1986, the maximum depths of cracks were 2.3 m and 2.14 m, respectively, the width of cracks was not larger than 1.0 mm; at the beginning of 2002, through the detection of new and old cracks by Huaihe River Basin Hydraulic Engineering Quality Inspection Center, the width of cracks was 0.05~0.45 mm. From the above detection results, the cracks at the downstream face of the Arch Dam are all surface cracks.

2.2 Objective causes for generation of cracks

2.2.1 Effect of Arch Dam type on dam deformation

The Arch Dam is an Arch Dam with the same thickness and large central angle. Take the arch ring at the elevation of 196.00 m as an example, its thickness is 6.1 m, its central radius is 86.75 m, and its central angle is 126 ° . According to design of the existing flat Arch Dam, the corresponding central angle should be about 80 ° , and the corresponding central radius should be 120.25 m. It is seen that under the same thickness and span of arch ring, the arch length of the Arch Dam is 22.87 m larger than that of flat Arch Dams, when the arch ring is acted by the same temperature rising load, the upward expansion of the Arch Dam will be much larger than that of flat Arch Dams, the central angles for 5/6 of the dam height of the Arch Dam are larger than 120 ° , the expansion of the arch ring will result in large tensile stresses near the arch abutment in the downstream dam face. Simultaneously, the Arch Dam is of large arch and central angle, resulting in the converse suspending degree of 1:0.33 towards the upstream for the left and right bank slope girders, under the self-weight load, the tensile stress of 0.7~0.8 MPa would occur in the downstream of left and right bank slopes, which would cause the upward displacement of the Arch Dam.

2.2.2 Effect of temperature change in the downstream dam face on stresses of Arch Dam

Water in Some River flows from north to south near the dam site. Direction of the central line of the Arch Dam is NE18 ° 25 ′ ,the downstream dam face of which is towards the west. During the high temperature period in summer, the sunlight is directly shining on the downstream dam face. During the period of empty reservoir, the upstream dam face was not shined, and owing to the large difference between day and night in the mountainous area, the temperature of the upstream dam face is much lower than that of the downstream dam face; furthermore, girders of both bank slopes are conversely suspended toward the upstream, the downstream dam face receives more heat from sunlight, thus the difference between the upstream and downstream dam faces. The temperature of the downstream dam face is larger than that of the upstream dam face, resulting in upward deformation of bank slope girders. Under the self-weight and temperature rising loads, the maximum tensile stress of the downstream dam face calculated by use of the multi-arch beam method is 3.56 MPa. The calculated results do not take into account effect of the direction of the Arch Dam and actual sunlight temperature difference.

Generally, owing to the restriction of types and direction of the Arch Dam, cracks will surely occur under the condition of empty reservoir and temperature rising. The actual operation is that the cracks at the left and right banks observed on Aug. 26, 1978 are resulted from the above causes. Owing to the restriction of upper arch rings, the deformation of bank slop girders towards the upstream is restricted, thus the tensile cracks did not extend towards the deep part of the dam. From the above, the cracks appeared at the later period in the downstream dam face are surface ones mostly caused by nonlinear temperature difference of dam faces.

2.3 3D FEM analysis

2.3.1 FEM model

The Arch Dam and the mass at both banks are regarded as an integral block to perform 3D finite element discretization. Along the dam height direction 18 layers are automatically divided and 5 layers are divided along the thickness direction, and subareas of different concrete materials are taken into account, that is, under the elevation of 172.0 m, concrete R250# is employed and above the elevation of 172.0 m, concrete R200# is employed. Faults F_2, F_{11}, F_{14}, F_{15}, F_{16}, F_{17}, F_{18} of rockmass are simulated. The Cartesian coordinates employed in the calculation are as follows: the direction of axis X is from the right bank to the left bank, the direction of axis Y is towards the upstream, and the direction of axis Z is vertically upward. The computation domain is as follows: the horizontal direction includes the Arch Dam and the dam abutment at both banks and the massif, and the length is 320 m, the longitudinal direction is 200 m in length and the vertical direction is 150 m in length. 9609 nodes and 8486 elements are divided. Fig. 2 shows the 3D FEM meshes.

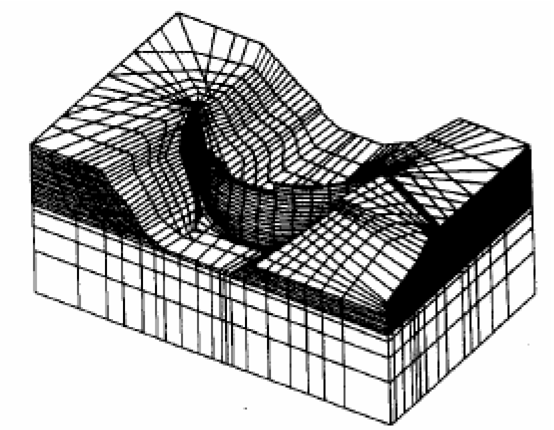

Fig. 2 3D FEM meshes of the Arch Dam

According to the dam materials, reinforcement materials, rockmass subareas and characteristics of faults, the main parameters are as follows: as regards the concrete 250# for dam, Ec = 2.85×10^4 MPa, $\mu = 0.167$, $\gamma = 2400$ kN/m^3, $f_c = 1.9$ MPa, $f_g = 22.0$ MPa; as regards the concrete 200# for dam, Ec = 2.60×10^4 MPa, $\mu = 0.167$, $\gamma = 2400$ kN/m^3, $f_c = 1.6$ MPa, $f_g = 17.5$ MPa. In which, Ec is the elastic modulus of the dam; μ is the Poisson's ratio; γ is the volumetric weight; f_c and f_g are the tensile and compression strengths of concrete, respectively.

2.3.2 Results of FEM analysis

In order to correctly know the deformation stress law of dam under the existing conditions, to assess whether the dam can effectively block the water or not and to judge the rehabilitation schemes for Arch Dams, it is necessary to perform 3D FEM analysis for the dam under the exiting conditions. Based on the current codes and combined the engineering practices, the operating conditions for calculation are as follows:

Operating condition 1: Normal water level (201.00m) + tail water level (161.50m) + normal temperature droping + self-weight + sediment pressure + uplift pressure

Operating condition 2: Dead water level (183.00 m) + tail water level (161.50 m) + normal temperature rising + self-weight + sediment pressure + uplift pressure

Based on the above FEM model and different operating conditions, loads affecting on the Arch Dam are calculated by use of 3D thin layer FEM program[3]. The maximum principal stress (the maximum compression stress), the minimum principal stress (the maximum tensile stress) of the dam abutment, dam toe, different arch rings and abutments at both banks as well as the occurrence position are obtained under different operating conditions, and the analysis of the calculated results is given below.

(1) Analysis of results for the operating condition 1

There are displacements of dam crest in the upstream face towards the river center (that is, the central line of the dam) at the left and right sides of spillway orifice. The displacements of the right and left ends are 2.33 mm and -2.79 mm, respectively (As for the displacements, the axial direction of the coordinates is positive.). the horizontal displacement of arch abutment at both banks is very small, about 0.1 mm. The maximum longitudinal displacement of the dam occurs the bottom surface of spillway of the central face of dam, and it is 6.2 mm, its direction is towards the downstream. The longitudinal displacement at the abutments at both banks is small, and it is less than 0.4 mm. The longitudinal displacement at the dam bottom is about 0.45 mm, and its direction is towards the downstream. The vertical displacement of the upstream dam face is 1.85 mm, the position is on the crest surface of dam crest spillways, and its direction is towards the downstream.

The maximum principal tensile stress in the upstream of dam occurs at the riverbed reach of the dam bottom, and it is 1.65 MPa. The horizontal positive stress ate the central section in the upstream of dam bottom is 1.16 MPa. Much larger stresses in the dam all occur near the dam bottom, the stresses at the abutment at both banks are all very small, and the tensile stress in the downstream face is only about 0.6 MPa, while the maximum principal compression stress is only 3.1MPa. The simulated results show that after cracks occur in the dam, the condition of normal water level + temperature droping has little effect on stress in the dam, and it does not result in the deterioration of stresses in the dam. Therefore, the dam can operate safely under the condition of normal water level.

(2) Analysis of results for the operating condition 2

The horizontal displacements of the dam are towards the both banks, and the maximum values (position of 1/4 of right and left dam reach) are -13.3 mm and 13.6 mm, respectively. The horizontal displacements at the abutments at the right and left banks are about 1.3～1.6 mm. Distortional deformation of the arch ring is caused. The maximum longitudinal displacement in the upstream face occurs near the spillways at the dam crest, up to 21.1 mm, and its direction is towards the upstream. The longitudinal displacements at both banks are less than 1 mm. The maximum vertical displacement in the upstream dam occurs at the middle part of dam crest, and it is 5.85 mm. It is seen that the dam is of large deformation under the condition of dead water level + temperature rising. The calculated results show that the stresses in the upstream dam face are smaller than those in the downstream face, the principal stresses mainly concentrate within certain area of dam end, and the maximum tensile stress is 1.9 MPa. The stresses in the middle of the dam are very small. The severe position of stress is mainly in the downstream face. Near the abutments at both banks, there exists an oblique tensile stress region at the middle and lower part of the dam, and generally, the horizontal tensile stress is about 2～3 MPa, with some values being up to 4.6 MPa, and the maximum vertical stress is also up to 4.2 MPa. It is seen that the direction of the principal tensile stress in the oblique large stress area tends to the vertical one.

In general, from the deformation and stress law, owing to that the cracks in the downstream dam face weaken the integral strength of the dam, the integrity of the dam becomes bad. If the situation of dead water level + temperature rising occurs again, the downstream dam face will still result in oblique cracks or the old cracks will further extend and develop. Therefore, it is necessary to reinforce the downstream dam face.

3 Researches on crack rehabilitation and practices

3.1 Crack rehabilitation schemes

From the measured temperatures of the Arch Dam as well as their analysis, it is seen that effect of sunlight in summer on temperature of the dam is significant. The satisfactory solution is that insulating layers are placed on the downstream face so that the temperature-droping night arrives before the daily high temperature from the sun spread on the dam surface concrete. Furthermore, after years' operation, deformation and forces in the Arch Dam exist. Cracks in certain positions of the dam will result in re-distribution of internal force fields with a certain extent. With regard to the reinforcement of downstream face, the early-constructed concrete does not share the bearing capacity with the dam body, thus there exist much smaller stress fields in the reinforcement. Only the external loads such as water levels, temperatures, etc. are changed, will the stress state in the reinforcement greatly change.

In order to know the internal stress in the dam after its reinforcement and to predict whether cracks will still occur or not, it is necessary to analyze the design operating conditions for rehabilitation schemes[4].

3.2 3D FEM analysis

The main processes of the 3D FEM nonlinear method are as follows: (1) Simulation of the formation of self-weight stress field of the foundation (At this time, there is no construction of dam body.); (2) The dam body is grouted by segmentation of the dam, and the self-weight of the dam is added; (3) The abutments are closed, and cracks in the dam are simulated; (4) Loads such as water, sand, temperature, etc. are added (normal operating water level); (5) Pneumatically placed concrete is added, and temperature field after adding heat insulating materials is also added; (6) the total accumulated deformation and stress fields of the dam are calculated under the design operating loads. Because of the obvious change of temperature fields of the dam after adding heat insulating materials, the original temperature load method determined according to the codes for Arch Dams is not applicable. Therefore, it needs to calculate the temperature fields after the reinforcement. The calculated results show that after the reinforcement, the temperature fields in the dam have great change. Especially, as for the middle and lower part of the dam with many cracks and the part with large tensile stress, the temperature and temperature gradient have great decrease, and it is favorable to the decrease of temperature stress. In order to compare with the stress in the dam before reinforcement, the operating conditions are as follows:

Operating condition 3: design normal water level (201.00 m) + tail water level (161.50 m) + the calculated temperature field in Jan. + self-weight + sediment pressure + uplift pressure

Operating condition 4: design dead water level (183.00 m) + tail water level (161.50 m) + the calculated temperature field in July +self-weight + sediment pressure + uplift pressure.

By use of the above FEM model and parameters, the following results are calculated with regard to the operating conditions 3 and 4.

3.2.1 Analysis of results of operating condition 3

The calculated results show that under the design normal water level and temperature in Jan., the reinforced dam body has shrinkage deformation along the horizontal direction. There are displacements towards the dam center at the top of spillway orifices at the right and left dam reaches, and they are 4.26 mm and -2.76 mm, respectively. The maximum longitudinal displacement is -8.13 mm, and it occurs near the right part of the dam crest center. The displacements at the abutments at both banks are very small, and they are less than 0.5 mm. The vertical deformation in the upstream dam face is mainly downward displacement. The displacement of the dam crest is 3.43 mm. In general, the deformation of the reinforced dam has little deformation under the design water level and it is allowable.

The principal tensile stresses in the upstream dam face concentrate near the abutments in the middle and lower part of the dam and in the riverbed. The maximum principal tensile stress occurs near the abutment at the right bank in the dam bottom, and the principal tensile stress is 2.43 MPa. The principal tensile stress in the downstream dam face is 1.45 MPa, and it occurs in the reinforced area of the abutments at both banks in the dam bottom. The principal stress in the dam body is not large, only 2.17 MPa. It is seen that only a small area with the principle stresses of 2.0～2.4 MPa is in the upstream face of abutments, and the stress in the dam body is not large.

3.2.2 Analysis of results of operating condition 4

The laws revealed by the results of displacements show that the horizontal displacements of the dam body are the ones towards the banks occurred at the position of 1/4 of the Arch Dam crest, and the maximum values for the right and left dam crests are -9.53 mm and 10.07 mm, respectively. The maximum longitudinal displacement is 15.14 mm, and it occurred at the top of spillways of dam crest. The longitudinal displacement at the abutments at both banks is very small, and it is about 1 mm. The maximum value is only 3.56 mm. Compared with the values before reinforcement under the condition of dead water level + temperature rising, they have a great decrease. For example, the longitudinal displacement is reduced to 15.14 mm from 21.1 mm. It is seen that effect of the insulating material and reinforcement measures in the downstream dam face on dam deformation is obvious.

The calculated results show that after the heat insulating materials are employed; the internal stresses in the dam have a great decrease. The principal stress in the upstream dam face is mainly concentrate within the certain area at the abutments at both banks, and it is 1.45 MPa. The stresses in most areas of upstream face are all very small, and the principal tensile area in the downstream face is within the oblique region near the abutment at both banks, the maximum stress is up to 2.91 MPa, and its direction is mainly vertical. Because the design tensile strength of the reinforced steel fiber concrete is up to 3.0 MPa and after the heat insulating measures are performed, the strength of the dam can be ensured under the condition of dead water level + temperature in July, and no cracks will occur.

3.3 Crack rehabilitation practices

The rehabilitation work of the Arch Dam began in Oct. 2004 and completed in Dec. 2005[5]. At first, steel fiber concrete materials are employed for dam reinforcement. In order to ensure the engineering quality, the employed steel fibers are the shear pattern with claws on both ends. According to different strength requirements of different reinforcement parts, the steel fibers with different dimensions are employed, it is 0.5～1.0 m in thickness from the dam crest to the dam bottom. As for the outer surface above the elevation of 183.0 m in the upstream and downstream of the dam, polyaminoester urethane foam (PUF) 5 cm in thickness is employed as the heat insulating materials. After about 5 s when the PUF is placed on the surface of structures, polyaminoester foam heat insulating layer is formed. Its coefficient of heat conductivity is only 1.3% of that of the concrete. Good heat insulating materials will obviously reduce temperature stress of the dam.

In order to verify the effectiveness of dam rehabilitation, stress-strain gauges are arranged in different positions in the downstream dam face to observe stress-strain situation of steel fiber concrete; simultaneously, thermometers are arranged at different elevations in the upstream and downstream faces to monitor the effectiveness of heat insulating materials[6]. Through the analysis of the observed data during the construction period and the initial operating period, the concrete stresses of the dam have obvious improvement, change of the temperature fields is normal, with the maximum value being 23℃ (during the initial operating period of the Reservoir), and the maximum tensile stress is 1.32 MPa. In addition, the in-situ quality inspection results show that there are no obvious cracks, the seepage phenomenon in the downstream face has obvious improvement, and the purpose of crack rehabilitation is reached.

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