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Simulation and crack analysis of the whole process of a Roller **Compacted Concrete dam during construction and operation**

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Abstract: The structural safety calibration is an essential problem of Roller Compacted Concrete (RCC) dams. Due to the simulation complexity of RCC dams and shortcomings of conventional methods, usually, the actual mechanics state cannot be obtained easily by the numerical methods. In this paper, a RCC gravity arch dam in Laos is taken for an example, the simulation program has been developed, and three-dimensional simulation analysis of the temperature field and stress-strain field of the whole process of RCC dam during construction and operation is carried out. The composite contact crack element is proposed to simulate the complicated mechanical behaviors of various kinds of joints and cracks. The research results show that the simulation results of the temperature field, the stress-strain field and cracking are close to the monitoring data, the space-time evolution of the temperature field and the stress-strain field of the RCC dam are obtained. The whole working state of the RCC dam is evaluated, and the causes of the dam cracks are revealed. The research results are adopted by the design institute, which is of great importance to ensure the engineering safety of design, construction, impoundment and operation.

1. Introduction

Japan is the country where the world's first RCC dam Shimajigawa (H=89m) was constructed in 1980[1]. Until now, the highest RCC dam is China's Huangdeng RCC dam, which has a maximum height of 203m with a crest length of about 464m at elevation 1625m. Because of simple temperature control measures, rapid construction, little cement consumption and minimal investment of RCC dams, the size and height of RCC dams have been increased in a very significant way. According to the statistics of the 6th international symposium on RCC dams, Zaragoza, 2012, at the end of the year 2011, the countries with a great number of RCC dams running and under construction are: China with 50 dams, Japan 150, the United States 46, Brazil 44, Spain 27 dams. RCC dams in these five countries accounted for more than 60% of the total numbers in the world. These countries play a leading role in the construction of RCC dams [2]. However, structural joints and induced joints are designed, also, special construction techniques such as thin continuous rolling, joint grouting and storing water without the second cooling are adopted, and the stress state is complicated. The structural safety of RCC dams is very important, therefore, the coupling simulation analysis of the temperature field and the stress-strain field of RCC dams during the whole process of construction and operation is needed.

In the simulation analysis of RCC dams, the application of the finite element method is most popular and mature. In the last decades, many researchers have paid attention to the application of FEM. Zhu systematically studied the basic principle of the temperature field and creep stress field in massive

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concrete structures using finite element method and compiled calculation program [3]. Huang et al. evaluated the temperature control measures of RCC gravity dam according to the simulation analysis results of the temperature field and creep stress field by using three-dimensional finite element method [4]. Zhou et al. developed the simulation programs for the temperature field and the stress field in the construction of RCC dams, and proposed some improved control measures of concrete temperature to solve the existing problems in Guandi RCC dam [5]. Chen and Zhang completed the three-dimensional simulation of the thermal stress in a high RCC dam by using the relocating mesh method [6-7]. Su et al. carried out an integrated simulation of the whole process including temperature, seepage, and stress by using finite element method, and the distribution laws of the temperature field, seepage field and stress field was obtained [8]. J. Noorzaeia et al. developed a two-dimensional finite element code for the thermal and structural analysis of RCC dams, the finite element code was verification through the Kinta RCC gravity dam [9]. Miguel Cervera developed a numerical procedure for the simulation of the construction process of RCC dams, and the Urugua-1' RCC dam is used to perform the corresponding analyses, and the thermochemical and the mechanical aspects of the simulation of the construction process are presented in paper [10, 11]. Abdulrazeg, AA et al. carried out a combined thermal and mechanical action in RCC dam analysis using a three-dimensional finite element method [12].

In recent years, a novel method named composite element method (CEM) was proposed by Chen [13]. The method can well treat the temperature field and creep stress field simulation problem of lift joints in RCC dams. The method was first applied in thermal simulation analysis of the Guanzhao RCC dam in paper [14]. The lift joint segments are embedded within the composite elements. The governing equation established on the variation principle is similar to that of the finite element method. The study shows the validity and merits of the composite element algorithm. Then, the method is applied in the simulation and feedback analysis of the temperature field of the Xiaowan 22# dam monolith during the construction period, and the calculation results tallies with the monitoring results well, which is proven to be feasible and effective. The research shows that the CEM is suitable for the simulation analysis of the temperature field [15]. The CEM can be expected to be used in complicated simulation analysis of the whole process of RCC dams during construction and operation.

Throughout the above numerical simulation methods, there are the following deficiencies according to preliminary researches: (1) Simulation of pouring process and safety evaluation of operation period are not closely linked; (2) Principle that regards the dam foundation and dam as a whole to conduct the research has not been implemented thoroughly; (3) Study on the coupling between the temperature field and stress-strain field is not in-depth.

In this paper, the simulation analysis principle of the whole process of the temperature field and creep stress-strain field is introduced, a composite contact crack element model is proposed, and the simulation program has been developed. Then, a RCC gravity arch dam in Laos is taken for an example, and a complex three-dimensional finite element model coupling the dam body and the foundation is established. According to the actual dam construction and water storage information, the whole simulation during the construction to the operation is studied. The temperature space-time evolution regularity of the RCC dam is obtained considering adiabatic temperature rise of concrete, air temperature, and water temperature. The stress-strain space-time evolution regularity of the RCC dam who suffered the upstream water pressure, gravity, and temperature load is obtained as well, considering the variation of elastic modulus, creep, autogenous volume deformation of concrete. The structural joints, induced joints, cracks are simulated by the proposed composite contact crack element. The simulation values of the temperature field and stress-strain field tallies well with the monitoring results. The simulation results reveal the space-time evolution of the whole process of the RCC dam really. Then, the whole working state of the RCC dam is evaluated, the causes of the dam cracks are revealed, which provides guidance and references for design, construction, impoundment and operation of the RCC dam.

2. The basic principles

2.1 The temperature field

The heat conduction equation can be written in the following formula:

$$\frac{\partial T}{\partial \tau} = k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{\partial \theta}{\partial \tau}$$
(1)

Where: *T*-temperature; *k*-thermal diffusivity; θ -hydrate heat; *c*-specific heat; ρ -density; τ -time. Which is subject to appropriate initial condition:

$$T\Big|_{\tau=0} = T_0(x, y, z)$$
(2)

and boundary conditions:

$$T\Big|_{\Gamma_1} = T_b \quad (\text{first type}) \tag{3}$$

$$\lambda \frac{\partial T}{\partial \{n\}}\Big|_{\Gamma_2} = -\beta(T - T_a) \quad (\text{ second type})$$
(4)

$$\lambda \frac{\partial T}{\partial \{n\}}\Big|_{\Gamma_3} = 0 \quad (\text{third type}) \tag{5}$$

In which $\{n\}^T = [l_x, l_y, l_z]$ are direction cosines of the external normal to the boundary.

2.2 The stress-strain field

To consider the effects of temperature on elastic modulus and creep behavior of concrete, the incremental method is used to calculate. Time τ is divided into a number of time periods $\Delta \tau_n$ (n=1,2,...,n).

The strain increment in the time period $\Delta \tau_n$ is:

$$\left\{\Delta\varepsilon_{n}\right\} = \left\{\Delta\varepsilon_{n}^{e}\right\} + \left\{\Delta\varepsilon_{n}^{c}\right\} + \left\{\Delta\varepsilon_{n}^{T}\right\} + \left\{\Delta\varepsilon_{n}^{g}\right\} + \left\{\Delta\varepsilon_{n}^{g}\right\} + \left\{\Delta\varepsilon_{n}^{s}\right\}$$
(6)

In the formula, $\{\Delta \varepsilon_n^e\}$ —elastic strain increment; $\{\Delta \varepsilon_n^e\}$ —creep strain increment; $\{\Delta \varepsilon_n^T\}$ —temperature strain increment; $\{\Delta \varepsilon_n^g\}$ —autogenous volume strain increment; $\{\Delta \varepsilon_n^s\}$ —drying shrinkage strain increment.

Using an implicit method and assuming that stress rate is constant in the time period $\Delta \tau_n$, elastic strain increment $\{\Delta \varepsilon_n^e\}$ is got.

$$\left\{\Delta \varepsilon_n^{e}\right\} = \frac{1}{E\left(\overline{\tau_n}\right)} [Q] \{\Delta \sigma_n\}$$
⁽⁷⁾

In the formula, $E(\overline{\tau_n})$ is the elastic modulus in the middle time period and [Q] is expressed by formula (8) to the space problem.

$$[Q] = \begin{bmatrix} 1 & -\mu & -\mu & 0 & 0 & 0 \\ -\mu & 1 & -\mu & 0 & 0 & 0 \\ -\mu & -\mu & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2(1+\mu) & 0 & 0 \\ 0 & 0 & 0 & 0 & 2(1+\mu) & 0 \\ 0 & 0 & 0 & 0 & 0 & 2(1+\mu) \end{bmatrix}$$
(8)

Creep strain increment $\{\Delta \varepsilon_n^c\}$ can be evaluated by the following formula:

$$\left\{\Delta\varepsilon_{n}^{c}\right\} = \left\{\eta_{n}\right\} + C\left(t,\overline{\tau_{n}}\right)\left[Q\right]\left\{\Delta\sigma_{n}\right\}$$

$$\tag{9}$$

In the formula,

$$\{\eta_n\} = \sum_{s} \left(1 - e^{-r_s \Delta \tau_n}\right) \{\omega_{sn}\}$$
(10)

$$\{\omega_{sn}\} = \{\omega_{s,n-1}\} e^{-r_s \Delta \tau_{n-1}} + [Q] \{\Delta \sigma_{n-1}\} \Psi_s(\bar{\tau}_{n-1}) e^{-0.5r_s \Delta \tau_{n-1}}$$
(11)

Relationship between stress and strain increments is:

$$\{\Delta\sigma_n\} = \left[\overline{D}_n\right] \left(\{\Delta\varepsilon_n\} - \{\eta_n\} - \{\Delta\varepsilon_n^T\} - \{\Delta\varepsilon_n^g\} - \{\Delta\varepsilon_n^s\}\right)$$
(12)

In the formula,

$$\left[\overline{D}_{n}\right] = \overline{E}_{n} \left[Q\right]^{-1} \tag{13}$$

$$\overline{E}_{n} = \frac{E(\tau_{n})}{1 + E(\overline{\tau}_{n})C(t,\overline{\tau}_{n})}$$
(14)

Using encoding method to assemble node force and node load, global balance equation is got as following:

$$[K]\{\Delta\delta_n\} = \{\Delta P_n\}^L + \{\Delta P_n\}^c + \{\Delta P_n\}^T + \{\Delta P_n\}^g + \{\Delta P_n\}^s$$
(15)

In the formula, [K]—global stiffness matrix; $\{\Delta P_n\}^L$ —element node load increments caused by external load; $\{\Delta P_n\}^c$ —element node load increments caused by creep; $\{\Delta P_n\}^T$ —element node load increments caused by temperature; $\{\Delta P_n\}^s$ —element node load increments caused by autogenously volume deformation; $\{\Delta P_n\}^s$ —element node load increments caused by drying shrinkage deformation.

The node displacement increment $\{\Delta \delta_n\}$ can be solved by formula (15). Then the element stress increment can be calculated. Adding up the increment, element stress is expressed as follows:

$$\{\sigma_n\} = \{\Delta\sigma_1\} + \{\Delta\sigma_2\} + \ldots + \{\Delta\sigma_n\} = \sum\{\Delta\sigma_n\}$$
(16)

2.3 The composite contact crack element

2.3.1 Mechanical model

Repeated opening and closing of cracks are a kind of typical nonlinear contact problems. The nonlinear contact element is usually used to simulate the crack in the commercial finite element software. Because of the possible initial opening simulation and the convergence problem of nonlinear contact element and the complicated safety evaluation problem of RCC dams. The new crack element which called composite contact crack element is proposed, and shown in figure 1. It is a series composed of the contact component and the real concrete component. There are two rules are implied in the crack element model [18].



Figure 1. The crack element model

(1) The total strain of the crack element is divided into the contact component and the concrete component:

$$\{\Delta \varepsilon\}^n = \{\Delta \varepsilon\}^n_R + \{\Delta \varepsilon\}^n_C \tag{17}$$

In this formulation (17), the subscripts R and C represent the real concrete component and the contact component respectively.

(2) The total stress of the crack element is equal to the strain of both the contact component and the concrete component:

$$\{\Delta\sigma\}^n = \{\Delta\sigma\}^n_R = \{\Delta\sigma\}^n_C \tag{18}$$

The strain and stress of the crack component mentioned above are written in the global coordinate system. In order to deduce the formulation of the crack component, a local coordinate system is adopted, in which the local x direction is defined along the dip direction of the crack, and the local y direction is defined along the strike, and the local z direction is determined by the right-hand rule. Then, the strain and stress of the crack component can be transformed between the two coordinate systems:

$$\begin{cases} \{\Delta\varepsilon\}_{c} = [T]_{c} \{\Delta\varepsilon\}_{c} \\ \{\Delta\sigma\}_{c} = [T]_{c}^{T} \{\Delta\sigma\}_{c} \end{cases}$$
(19)

In the above formulation(19), the subscripts C and c represent the global and local coordinate systems respectively, and the matrix $[T]_c$ is determined by the dip and strike direction of the crack element.

According to the potential theory of elastic viscoplastic, the elastic viscoplastic constitutive relation of each component can be written as:

$$\{\Delta \boldsymbol{\sigma}\}_{n} = [\boldsymbol{D}]_{n} \left(\{\Delta \boldsymbol{\varepsilon}\}_{n} - \{\dot{\boldsymbol{\varepsilon}}_{vp}\}_{n} \Delta t_{n}\right)$$

$$(20)$$

or:

$$\left\{\Delta\boldsymbol{\varepsilon}\right\}_{n} = \left[\boldsymbol{D}\right]_{n}^{-1} \left\{\Delta\boldsymbol{\sigma}\right\}_{n} + \left\{\dot{\boldsymbol{\varepsilon}}_{vp}\right\}_{n} \Delta t_{n}$$
(21)

Where: [D]-elastic matrix; $\{\dot{\boldsymbol{\varepsilon}}_{v_p}\}_n$ -visco-plastic strain rate.

The visco-plastic strain rate can be calculated by formulation (22)

$$\{\dot{\boldsymbol{\varepsilon}}_{vp}\}_{n,R} = \gamma_R < F_R > \frac{\partial F_R}{\partial \{\boldsymbol{\sigma}\}}$$
(22)

The Drucker-Prager yield criterion is adopted for the concrete component, and the Mohr-Coulomb criterion is adopted for the crack component.

By substituting the constitutive equations of the above formulas of the concrete elements and crack elements into equation (18), the elastic-visco-plastic constitutive equation of the composite crack model can be obtained:

$$\{\Delta \boldsymbol{\varepsilon}\}_{n} = [\mathbf{S}]\{\Delta \boldsymbol{\sigma}\}_{n} + \{\Delta \boldsymbol{\varepsilon}_{vp}\}_{n}$$
(23)

where:

$$[\mathbf{S}] = [\mathbf{D}]_{\mathrm{R}}^{\mathrm{I}} + [\mathbf{T}]_{\mathrm{j}}^{\mathrm{I}} [\mathbf{D}]_{\mathrm{j}}^{\mathrm{I}} ([\mathbf{T}]_{\mathrm{j}}^{\mathrm{T}})^{\mathrm{I}}$$
(24)

$$\left\{\Delta\boldsymbol{\varepsilon}_{\rm vp}\right\}_{n} = \left\{\Delta\boldsymbol{\varepsilon}_{\rm vp}\right\}_{n,\rm R} + [\boldsymbol{T}]_{\rm j}^{-1} \left\{\Delta\boldsymbol{\varepsilon}_{\rm vp}\right\}_{n,\rm j} \tag{25}$$

2.3.2 Stress state of crack

Due to the complex stress state of the crack, which could be reflected by the dynamic change of the stiffness coefficient of the contact element. When the crack has not yet formed, it is in a cementation state, and the contact element stiffness is set to infinity. When the crack is treated with grouting, it is again in the cementation state, and the contact element stiffness can be calculated according to the elastic parameters of the cement material and the thickness of the grouting thin layer. After the crack is formed, the contact element stiffness is not compression. While the crack is open, the contact element stiffness is set to be 0.

Specific in the simulation calculation, it is assumed that the crack has not formed, and the contact element stiffness is a relatively great value. The tensile strength is the material actual value, which for the induced joints is 0, the transverse joints is the interface tensile strength of the new and old concrete,

and the dam cracks is the tensile strength of concrete in the actual age .The stress state of each Gaussian point of the composite contact element is obtained by simulation calculation in the process of the dam pouring and impoundment.

3. Engineering application

The RCC gravity arch dam is located in Laos, the maximum dam height is 100.5m, the arch crown cantilever base width is 42.0m, crest width is 6.0m, and crest centerline arc length is 234.8 m. In addition, the dam is designed with two structure joints and three induced joints, and the joint spacing is about 40m. The concrete pouring was started in January 2010, and completed pouring to elevation 1103.0m in February 19th, 2012.

In this paper, based on the mechanical model of complex materials and the deformation and failure mechanism, through the three-dimensional whole simulation on the temperature field and stress-strain field during construction and operation, the key technology problems such as temporal and spatial distribution of the temperature field and stress-strain field, the working state of structure joints and induced joints are carried out. Consequently, resolving the problems of the RCC dam in the design, construction and operation period, saving investment and ensuring the safety of the project.

3.1 Calculation model

The FEM calculation model of the RCC dam is shown as Figure 2 and Figure 3, the mesh sizes of the dam has to be 0.8m or so in the height direction, 2.0m or so in the longitudinal direction, and 5m or so in the transverse direction. All the existing cracks and the structure joints, as well as the bottom induced joints are simulated with the composite crack element proposed above. The total number of elements is 264934, and the total number of nodes is 235751. The X-axis points to the left bank, the Y-axis is along the river, and points upstream for positive; the Z-axis is upright.



Figure 2. FEM mesh of the dam



Figure 3. FEM mesh of the dam base

3.2 Analysis Basis

3.2.1 Mechanical properties of rock

The main mechanical parameters of the rock mass are listed in table 1. Table 1. Mechanical parameters of rock mass

	1			
	μ		E ₀ (Gpa)	
Name of material	Slightly weathered~ Fresh	Weak weathering	Slightly weathered ~Fresh	Weak weathering
Feldspar-quartz sandstone/Quartz sandstone	0.20	0.24	10	7
Argillaceous siltstone	0.24	0.26	7	5
Silty mudstone	0.26	0.285	5	3

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Concrete Parameters	C ₁₈₀ 20W4	C ₁₈₀ 15W4	C18020W8F50
Adiabatic temperature rise θ_0 (°C)	$\theta_t = \frac{20.24t}{3.051+t}$	$\theta_t = \frac{16.84t}{1.303 + t}$	$\theta_t = \frac{21.74t}{2.035 + t}$
Thermal conductivity $\lambda(kJ/(m \cdot h \cdot ^{\circ}C))$	11.632	11.793	12.865
Thermal diffusivity a $(\times 10^{-3} \text{m}^2/\text{h})$	5.0157	5.2419	5.6556
Bulk density γ (kg/m ³)	2399	2395	2388
Specific heat c (kJ/(kg·°C))	0.9667	0.9409	0.9526
Linear expansion coefficient α (×10 ⁻⁶ /°C)	10.285	10.071	10.129
Heat exchange coefficient $\beta (kJ/(m^2 \cdot h \cdot C))$		47.1	
Poisson ratio		0.189	
Tensile strength (Mpa)		1.2	
Elasticity modulus E (×10 ⁴ Mpa)	$E(t) = \frac{3.119t}{11.935 + t}$	$E(t) = \frac{3.345t}{20.751 + t}$	$E(t) = \frac{3.205t}{10.746 + t}$

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5.2.2 Inermal and mechanical properties of concrete	
$\mathbf{F} = \mathbf{F}$	
T_{1}	1.4.1

The main thermal and mechanical parameters of concrete are listed in table 2. Table 2. Thermal and mechanical parameters of concrete in the dam

3.2.3 Creep deformation of concrete

The following formula is used to fit the creep deformation of concrete:

$$C(t,\tau) = (x_1 + x_2 / \tau^{x_3})(1 - e^{-x_4(t-\tau)}) + (x_5 + x_6 / \tau^{x_7})(1 - e^{-x_8(t-\tau)}) + x_9 e^{-x_{10}\tau}(1 - e^{-x_{10}(t-\tau)})$$
(26)

In the formula (26), the parameters can be determined by experiment, the creep deformation of $C_{180}20W4$ is shown in figure 4.



3.2.4 Autogenous volume deformation of concrete

The values of autogenous volume deformation of concrete are fitted by the following formula:

$$\varepsilon = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5$$
(27)

Where: *t* is the age of the concrete.

The autogenous volume deformation of $C_{180}20W4$, $C_{180}15W4$ and $C_{180}20W8F50$ are shown in figure 5.

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Figure 5. Autogenous volume deformation of concrete

3.2.5 Meteorological conditions

The fitting curve of temperature based on monitoring data is shown as follows: $T = 20.35 + 4 \times \cos[0.0172 \times (t - 170)]$

(28)

Where: *t* is the total number of days after the starting day of January 10^{th} , 2010. The Meteorological conditions is shown as figure 6.



Figure 6. Diachronic curve of temperature

3.2.6 The process of dam placement

In accordance with the provided construction data, the process of placement distinguished by elevation is simulated. The thickness of concrete lift is 1.5m in strong constrained zones and 3.0m in weak constrained zones. The simulating placement process curve is shown as figure 7.



3.2.7 The process of water storage

The water storage process of the RCC dam is shown as figure 8. The water storage starts in February 28, 2012, and reaches to the normal water level 1100m in August 3, 2012.

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Figure 8. The curve of water storage process

3.2.8 Simulation of the reservoir water temperature

The first year in storage period, the water temperature is simulated based on the measured data. During the operating period, the following formulas are used [2].

The water temperature at depth *z*:

$$T(z,t) = T_m(z) + A(z)\cos[0.0172 \times (t-170)]$$
⁽²⁹⁾

The mean water temperature at depth *z*:

$$T_{m}(z) = c + (T_{s} - c)e^{-\alpha z}$$
(30)

$$c = (T_b - T_s g) / (1 - g)$$
(31)

$$g = e^{-0.04H}$$
 (32)

Annual amplitude of water temperature in a year:

$$A(z) = A_0 e^{-0.018z}$$
(33)

Where: *z* -water depth. *t* -time. *H* -depth of the reservoir. T_s - mean temperature of water on the surface, and 22.34 °C is used here according to provided data. T_b - mean water temperature at the bottom of reservoir, and 17.5 °C is used here according to experiences in the past. A_0 -amplitude of mean water temperature on the surface, and 2.5 °C is used here according to experiences in the past.

3.2.9 Distribution of the dam cracks

The construction is broken off on June 20th, 2010 because of the rainy season. The first crack is discovered on the surface on July 5th, 2010 and three more cracks are discovered continuously on July 15th, 2010. Crack propagation is not severe, and the width and depth of cracks are not large by observing. After water is allowed to pass the surface of the dam on July 24th, 2010, the condition of crack propagation got worse the next day. Cracks go deeper and wider, and two of them stretch themselves from upstream surface to downstream surface. Seven cracks are spotted from 0+050.500 (right bank) to 0+045.000 (left bank) at the elevation of 1044.4m. The width of cracks varies from 0.2mm to 2.5mm, and the depth ranges from 1m to 15m. Figure 9 shows the distribution of cracks at the elevation of 1044.4m, and figure 10 shows the crack in the dam.



Figure 9. Distribution of cracks at the elevation of 1044.4 m



Figure 10. Crack in the dam

3.2.10 Calculation schemes

The calculation program is COCE-TEMP/3D FEM, which was developed based on the basic principle of the temperature field and the stress-strain field. The software has unique technologies in treating the complex coupling simulation analysis of stress, seepage, temperature during pouring to operation process, crack opening and closing iterative problem in the dam, and the stability and the safety degree of the rock mass with the dam structure. The software has been successfully applied in a number of large water conservancy and hydropower engineering projects, for example: Xiaowan (294.5m high concrete arch dam) and Guangzhao (200.5m high RCC dam).

In this paper, according to the dam pouring and reservoir impoundment process data, the construction simulation time starts at the first block pouring day January 2010, and completes when the dam's last block pouring to elevation 1103.0m on February 19, 2012, the grouting of structure joints is simulated immediately. The operation period of storing water starts from February 28, 2012 to August 3, 2012, impounding to normal water level of 1100.0m. After that, assuming the water level is kept unchanged, predicting to long-term operation on January 1, 2025. In the simulation, the time step length of the temperature field, stress-strain field is 1 day in the construction and impounding period. As predicting to long-term running period during August 3, 2012 to January 1, 2025, the step length is 30 days.

3.3 Calculation results

3.3.1 Simulation analysis of dam temperature field

Figure 11 shows that the temperature of simulation calculation results and monitoring results of measuring point T1-9 (right bank 0+008.310, 24m from upstream, elevation 1035.0m) are changing consistent with time, The differential value between the simulation calculation and monitoring results is generally less than 3.0° C.



Figure 11. Temperature history curve of thermometer T1-9

After the concrete pouring, dam temperature rises rapidly under the action of hydration heat. Then, due to the pouring surface contact with the air cooling, the temperature decreases. After the surface is covered by the new pouring layer, temperature began to rebound. Later, depending on the thermal conductivity of concrete itself, slow temperature drops starting.

3.3.2 Simulation analysis of the stress-strain field

(1) Displacement distribution

Figure 12 shows that simulation values of measuring point PL02's deformation along the river direction are well matched with monitoring values.



Figure 12. Simulation and monitoring radial value of measuring point PL02 (0+0.000 profile, 6 m from upstream, elevation 1050 m)

Figure 13 shows the displacement distribution curves along the river of the characteristic points in different elevations of the downstream surface of the crown cantilever during the pouring process, the storage process and the long-term running period. We can get the following conclusions:



Figure 13. Displacement curves of the crown cantilever along the river,

Deformation of the characteristic points mainly downstream during the pouring process, and only partial elevations deform upstream. Deformation pointing upstream reaches the maximum value 0.9mm, appearing in the elevation of 1095m. While that pointing downstream increases gradually with the water storage. When the water storage reaches to the normal water level, the displacement along the river is 16.3mm, appearing in the elevation of 1086m. On January 1, 2025 (long-term run), the maximum displacement is 21.9mm, appearing in the elevation of 1086m.

(2) Stress distribution

The simulation and monitoring values of the compressive stress meter in the dam foundation are shown as follows (figure 14):



Figure 14. Simulation and monitoring values of the compressive stress meter Y4-3(dam heel)

1) During construction period (2010-01-29 ~ 2012-02-19), stress of the compressive stress meter Y4-3 on dam base surface is compressive. Simulation and monitoring values agree in law. As the dam rising, compressive stresses on dam base surface increase gradually.

2) During water storage period (2012-02-28 \sim 2012-08-03), the calculated compressive stress and the monitoring values at the dam heel progressively decrease.



Figure 15. Normal stress curves of foundation plane of the crown cantilever

Figure 15 shows that compressive stress in the range from 8 to 26.7m to the upstream surface changes little along the foundation plane. When pouring to a height of 39m, the compressive stress reaches the maximum value with -5.0MPa. With the water level rising and the dam continued pouring, compressive stress in the dam heel gradually decreases while that in the dam toe gradually increases. When pouring to the crest in the elevation of 1103m and storing water to the normal water level 1100m, tensile stress appears in the dam heel. When finishing the pouring process and storing water to the elevation of 1060m, compressive stress in the dam toe is equal to it in the dam heel. Then, the former exceeds the latter as the water level rising. Tensile stress in the dam heel is 2.0MPa while compressive stress in the dam toe is 3.4MPa when pouring to the crest in the elevation of 1103m and storing water to the normal water level 1100m, and they are respectively 4.1MPa, 3.1MPa at the end of the prediction long-term running period.

(3) Stress state of cracks

Stress state of major cracks shows that larger tensile stress near the upstream and downstream of cracks which at the riverbed dam section is of wide distribution along the height, and it occurred mainly in July 2010 (see figure 16 and 18). Larger tensile stress in the middle of cracks occurred only from the height of 1030m to the height of 1040m, and it occurred around July 2010 (figure.17). Results show that water went through the dam and dam's temperature dropped during the flood period in 2010 results in crack through the dam near the elevation of 1040m.



Figure 16. Normal stress curves of upstream points on right bank 0+017.600 crack



Figure 17. Normal stress curves of middle points on right bank 0+017.600 crack



Figure 18. Normal stress curves of downstream points on right bank 0+017.600 crack

4. Conclusions

After the three-dimensional integrated simulation analysis of the whole process of the construction and operation of the RCC dam, the following conclusions can be drawn:

(1) During the construction period and impoundment period, the results of the temperature simulation value of the measuring point are consistent with the monitoring results. The temperature field simulation results well reflected the change process with time and the distribution rule in space of the actual dam body temperature field.

(2) After the impoundment period, the dam deformation along the river all points downstream. The maximum deformation along the river is approximately 16mm which takes place around elevation 1080m. Vertical deformation all points down and decreases with the increase of elevation.

(3) After the impoundment period, under the water pressure and temperature load, tensile stress concentration takes place in the dam heel while compressive stress concentration takes place in the dam toe. With the gradual cooling of dam concrete, there will be partly tensile stress inside the dam at elevation 1030m while induced joints, cracks and structure joints open partly in the riverbed dam blocks, and the normal stress is approximately 0MPa.

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(4) Normal stress curves of major cracks reveal that larger tensile stress near the upstream and downstream of cracks is of wide distribution along the height, and it occurred mainly in July 2010. Larger tensile stress in the middle of cracks occurred only from the elevation of 1030m to the elevation of 1040m, and it occurred around July 2010. Results show that water went through the dam and dam's temperature dropped during the flood period in July 2010 results in crack through the dam near the elevation of 1040m.

The above research shows that the simulation results reflect the actual temperature, stress-strain, and the dam structure joints, induced joints, cracks evolution of space and time, which provides a reference for the design, construction, impoundment and operation.

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