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Simulation analysis of crack cause of concrete overflow dam for Hadashan Hydro Project by 3-D FEM

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Abstract

This paper is mainly to study the cracking reasons for concrete overflow dam of Hadashan Hydro Project. The three-dimensional finite element method (3-D FEM) is developed to simulation analysis the temperature and thermal stress distribution in the concrete overflow dam during the construction period. The results show that the crack of the concrete overflow dam is temperature crack, mainly due to the combined action of the internal thermal gradient and the external restraints; and dramatic changes in ambient temperature exacerbate cracking of early-age concrete. Finally, the results are applied to provide some references for the construction in the related fields.

Keywords: concrete overflow dam; cracking; temperature field; creep stress field; 3-D FEM

1. Introduction

The cause analysis of cracks in concrete overflow dam plays an important role on construction phase. In concrete overflow dams, the concrete temperature rising caused by the cement hydration, coupled with the low conductivity of concrete and the quick construction processes give rise to high thermal gradients between the interior and exterior of the dam. Cracks will develop in the body dam because of the existence of this temperature field. If the cracks do not meet the requirements of the regulatory, such as *specifications for hydraulic concrete construction*[1], it will affect the safety of the concrete overflow dam. Therefore, it is necessary to study the reason-generating of these cracks.

The FEM can be used to analyze the reason-generating of cracks in the concrete overflow dams effectively on the construction phase. Ishikawa[2] presented an example shown that ADINA was applied to the thermal stress analysis of a concrete dam. Saetta[3] presented a numerical procedure based on the FEM for the stress-strain analysis of concrete structure exposed to time- and space-variable thermal loads. A two-dimensional constitutive model considering time and temperature dependent mechanical properties was carried out by Milton[4] using for concrete gravity dams. Chen[5] carried out a three-dimensional finite element relocating mesh method for simulation analysis of temperature and thermal stress distribution in a

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roller compacted dam during the construction period. The actual climatic conditions and thermal properties of the materials were considered by Noorzaei[6] in the analysis. A finite element code was applied to the real full-scale problem to determine the impact of the placement schedule on the thermal response of roller compacted concrete dam by Jaafar[7]. Cai[8] developed a smeared crack model, based on non-linear fracture mechanics, which allows for either linear or bilinear softening and assumes shear retention dependent on the strain normal to a crack. A thermo-mechanical numerical model was used to simulate the early-age concrete behaviour of the specimen and a new methodology based on ambient vibration is proposed to test to characterize the evolution of E-modulus of concrete right after casting by Azenha[9,10]. However, few investigations have been focused on the three-dimensional finite element analysis of the causes of cracks in the concrete overflow dams.

The strength grade of the concrete is C15F50W6 which was applied in the concrete overflow dam of Hadashan Hydropower Station. The concrete overflow dam of the third layer was opened at 11:30 on June 7th 2008, and was closed at 2:30 on June 9th 2008, the pouring elevation is 123.5-125.5 m and thickness is 2 m. A crack was found in bottom plate of the concrete overflow dam of the third layer which parallels to dam axis on June 23rd 2008, the width of it ranges from 0.4 mm to 0.7 mm, and the depth about is 1m.

A 3-D FEM for an analysis of the reasons for cracks of pouring blocks in the concrete overflow dam exposed to time-variable environmental conditions is presented in this work. This model takes into the conditions of the seasonal and daily variation of temperature account which can lead to cracks generation in concrete structures. The simulation results in a concrete overflow dam can instruct the construction of the similar projects.

2. Finite Element Model

The crack location is shown in Fig. 1.

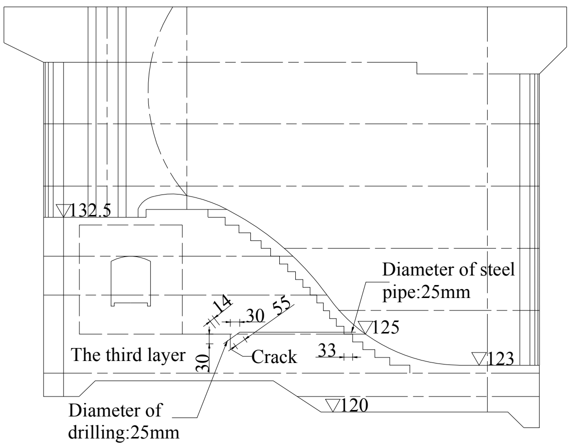


Fig. 1 Diagram of crack

2.1. Finite element mesh model

The three-dimensional finite element mesh model of the concrete overflow dam is indicated in Fig. 2.

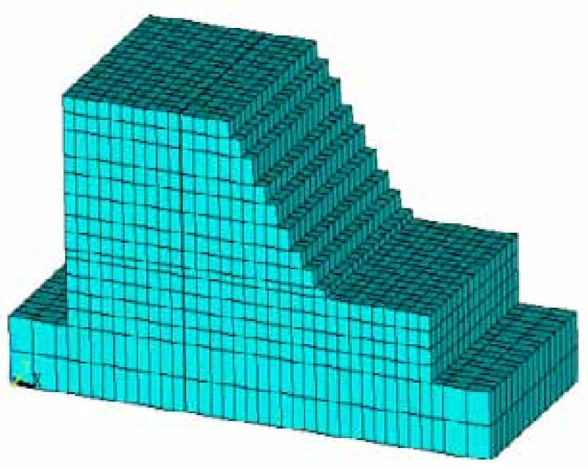


Fig. 2 Finite element mesh model of the concrete overflow dam.

2.2. Calculation conditions

Construction progress of the concrete overflow dam is shown in Table 1. The ten-day average temperature and month average temperature for many years in construction area are shown in table 2. Concrete material properties are shown in Table 3. The actual temperature of concrete pouring is shown in Table 4. Calculation formulae of material properties are shown in Table 5.

Table 1 Construction progress of the concrete overflow dam

Serial number	Construction parts	Casting date	Form removal date	Elevation (m)
1	The first layer	13/05/2008～14/05/2008	17/05/2008	119.00～121.00
2	The second layer	23/05/2008～26/05/2008	31/05/2008	121.00～123.50
3	The third layer	07/06/2008～09/06/2008	13/06/2008	123.50～125.50
4	The fourth layer	06/07/2008～07/07/2008	12/07/2008	125.50～128.00
5	The fifth layer	28/07/2008～29/07/2008	03/08/2008	128.00～129.00
6	The sixth layer	04/08/2008～05/08/2008	08/08/2008	129.00～130.50
7	The seventh layer	09/08/2008～11/08/2008	16/08/2008	130.50～132.50

Table 2 Average temperature of the construction area (℃)

Month	Average No. 01-10	Average No. 11-20	Average No. 21-30	Monthly average temperature	Annual mean temperature
January	-15	-15	-13.1	-14.4	8.8
February	-16	-13.6	-10.1	-13.2	
March	-9.2	-1.4	4.8	-1.9	
April	10	25.6	15.9	17.2	
May	18.2	18.5	20.9	19.2	
June	15.6	22.2	24.4	20.7	
July	27.7	25	27.1	26.6	
August	28.1	23.4	28.8	26.8	
September	27.3	26.1	25.7	26.4	
October	15.6	16.4	10.8	14.3	
November	3.5	-1.8	-7.9	-2.1	
December	-11	-15.6	-15.2	-13.9	

Table 3 Concrete Material properties

Parameters	Units	Values
Poisson's ratio		0.167
Weight capacity	kg/m^3	2400
Thermal diffusivity	m^2/d	0.094
Thermal conductivity	W/m · K	8.600
Specific heat	kJ/kg · K	0.934
Linear expansion coefficient	10^{-6}/℃	9.100

Table 4 The actual pouring temperature of the concrete (℃)

Dam block	No.2
The first layer	18
The second layer	19
The third layer	18
The fourth layer	18
The fifth floor	21
The sixth floor	21
The seventh layer	21
The eighth floor	/

Table 5 Calculation formulae of C15 concrete parameters

Category	Formulae
Elastic modulus (10^{10}Pa)	$E=2.26\left(1-\exp\left(-0.1902t^{0.4947}\right)\right)$
Concrete creep (1/Pa)	$C(t,\tau)=\left(9.69\times10^{-12}+8.92\times10^{-11}/\tau^{0.45}\right)\left(1-\exp\left(-0.3(t-\tau)\right)\right)$ $+\left(2.19\times10^{-11}+3.73\times10^{-11}/\tau^{0.45}\right)\left(1-\exp\left(-0.005(t-\tau)\right)\right)$
Adiabatic temperature rise (℃)	$T=25\left(1-\exp\left(-0.2627t^{0.5770}\right)\right)$

3. Results and Discussion

The main reason for producing cracks of early-age concrete is the heat generated by hydration. The cement hydration is an exothermic reaction and, consequently, a large amount of heat is generated during the process, which caused temperature rise in early-age concrete under consideration (see Fig. 3). Temperature rise causes the concrete to expand equally and uninhibited in all directions. However in practice conditions, they are far from this ideal, particularly in large concrete structures, which maybe create temperature differences between internal and external concrete. Early-age thermal cracking is the result of differential expansion and contraction of the element due to temperature changes within the member. In other words, the strains caused by this expansion and/or contraction, exceed the tensile capacity of the concrete and any restraints in place that prevent this expansion/contraction from freely occurring cause the member to crack (see Fig. 4, Fig. 5, Fig. 6 and Fig. 7).

Cracks form during both the heating and cooling phases of the hydration process (see Fig. 3). During the heating phase, when the concrete has been poured and hydration has begun, some heat is retained inside of the concrete member, which causes temperature rise in the material. At this point, the heat generation rate is greater than heat loss rate and the concrete would expand under ideal and no any restraint conditions. In fact, a section is always at least partly restrained, and the heat is dissipated from the concrete surface at a quicker rate than interior, which implies having a non-uniform expansion in the section. Since the cooler outer areas of the element are not expanding at the same rate as the hotter inner sections, the expansion of the interior and the resistance to thermally induced movement can lead to a buildup of tensile stress in the surface zone, which eventually causes the formation of concrete surface cracks. As mentioned, this will only occur if the tensile stress on the surface exceeds the tensile capacity of the concrete at that point in time. Once the concrete enters the cooling phase (see Fig. 3), under ideal conditions where no restraint or temperature differentials exist, the concrete element would contract equally in all directions. However, the issues discussed earlier with regard to the expansion of the element during the heating phase, cause internal restraint and prevent this contraction from occurring freely. The higher heat dissipation rate of the surface layers compared to inner core of the concrete leads to the surface setting and hardening before the core has cooled down. The already stiff outer layers restrain the interior of the element as it begins to contract upon cooling. This induces a tensile stress within the material and once the tensile capacity of the concrete is exceeded, internal cracks occur within the element.

The dramatic changes of ambient temperature aggravate the cracking process of early-age concrete. There is internal heat generating inside the early-age concrete which can be controlled by the hydration reaction. The strains caused by this heat which exceeds the tensile capacity of the concrete and any restraints causes the formation of surface cracks on the concrete. The maximum temperature of concrete occurred approximately 42℃ after casting four days, while the minimum of ambient temperature was approximately 17℃ at the same time, therefore, the concrete was at a higher temperature than the ambient one (see Fig. 3). Owing to dramatic changes in the ambient temperature, the temperature inside the concrete was much greater than the outside one (see Fig. 4, Fig. 5, Fig. 6 and Fig. 7). When no insulation measures are to be taken, the temperature difference would have result the increase of the concrete surface stress. The further propagation of concrete surface cracks occurred. The results showed that the sudden changes of ambient temperature are an important reason for the propagation of the early-age concrete surface cracks, when insulation effective measures were not to be taken.

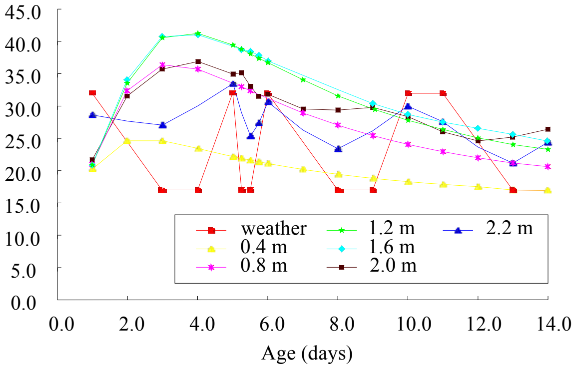
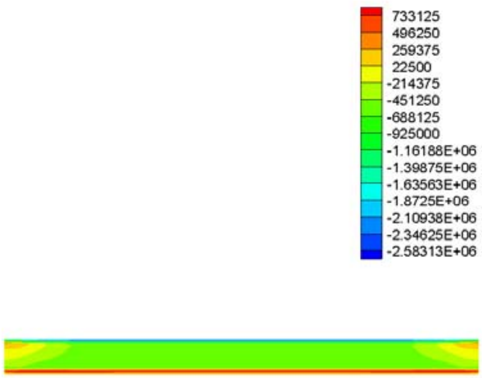


Fig. 3 Temperature curve at different distances from the concrete surface in the third layer of the concrete overflow dam



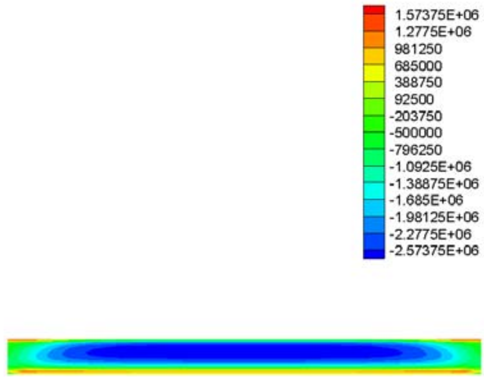
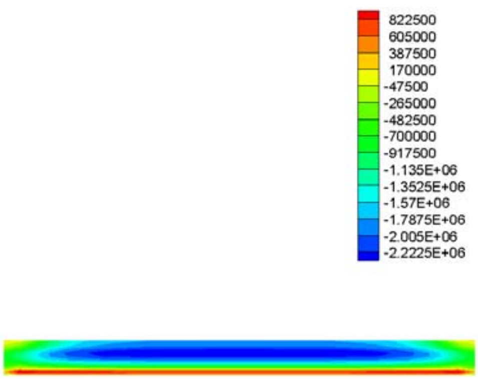


Fig. 4 Stress distribution of the third layer of concrete overflow dam, when t = 1d; Fig. 5 Stress distribution of the third layer of concrete overflow dam, when t = 3d.



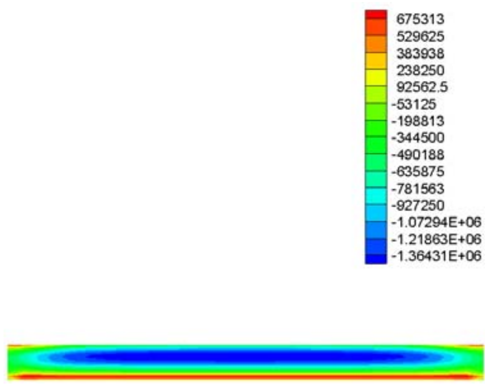


Fig. 6 Stress distribution of the third layer of concrete overflow dam, when t = 5d; Fig. 7 Stress distribution of the third layer of concrete overflow dam, when t = 7d.

4. Conclusion

In order to minimize the risk of thermal cracking, the knowledge that temperature profile of a concrete section during construction period is needed. Based on this study, the following conclusions have been made:

(1) The strains caused by temperature field which have exceeded the tensile capacity of the concrete are the main cracking reason of the early-age concrete.

(2) With the dramatic changes of ambient temperature conditions, the important reason of cracking propagation on the surface of early-age concrete is no effective insulation measures.

The results obtained in this paper can be instructed the construction of similar projects.

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