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Research on Key Technology of Temperature Control in the Whole Process of RCC Dam Construction

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Abstract. In recent years, China's hydropower station projects are mainly concentrated in the southwest region. These huge projects are facing the tight construction period and complex construction conditions, especially strong wind, dry and hot, single-point rainstorm, low early-stage strength and remarkable later-stage temperature rise of roller-compacted concrete (RCC) dam, it is very difficult to control temperature and prevent concrete dam from cracking. Based on the development status of intelligent temperature control for concrete dam, we innovatively carried out a study on the intelligent whole-process temperature control during the construction of RCC dam in combination with the actual situations of projects in the southwest region and the current research progresses; proposes the overall framework, roadmap and various research issues; puts forward a method to obtain the real crack-resistance properties through combining TSTM with simulation calculation; and realizes the coupling regulation with intelligent temperature control through creating feedback-simulation cloud platform; finally, the dynamic whole-process intelligent feedback control can be realized for concrete dam from raw materials to mixing, transportation, pouring, temperature monitoring, cooling water supply, protection and maintenance, so as to guarantee the construction quality of RCC dam under complex and serve conditions.

Keywords. Intelligent temperature control, temperature control for crack prevention, dry-hot valley, intelligent construction, roller compacted concrete

1. Introduction

Currently, the construction industry is facing an intelligence and information tendency in the world; most of countries are intensively researching on the digital development mode. It is imperative to apply intelligent technology in hydropower construction, which will promote transformation and upgrading of this field in China, and play an important role in the whole life cycle of hydropower projects.

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At present, the project is characterized by the tight construction period and complex construction conditions, especially strong wind, dry and hot, single-point rainstorm, low early-stage strength and remarkable later-stage temperature rise of RCC dam making it extremely difficult to prevent cracking through controlling temperature, which brings considerable challenges to construction management, construction quality and progress control. The intelligent temperature-control technology is a component of the construction of concrete dam, which can greatly improve the construction quality, technical level and management efficiency during dam construction, and enhance the core competitiveness in term of hydropower project construction. It has broad application prospects in similar projects.

2. Key Issues

Since the whole-process application of intelligent temperature control was initiated in Huangdeng Hydropower Project, over 20 key temperature-control elements can be comprehensively collected and managed in real time, key temperature-control indicators can be comprehensively analyzed, evaluated and early warned, and the intelligent control has been realized for water cooling, the "Huangdeng Mode" was set for the intelligent construction of RCC dam with remarkable benefits achieved. Many dam projects, such as Fengman Reconstruction, Touba, Wudongde, Baihetan and DG, were built in succession with the intelligent whole-process temperature-control technology applied [1,2,3]. With consideration of the actual situations of the current research progresses in China, some issues still need to be solved or further improved in the field of intelligent temperature control, including: (1) The intelligent digital control is still unavailable for the concrete production and mixing system; the evaluation, early warning and intelligent feedback are still absent for the outlet temperature control; (2) As Touba Project is a dry and hot valley facing intense radiation, it is necessary to develop the intelligent control specific to poured concrete environment and characteristic control model, and then apply in the construction; (3) Currently, the intelligent water cooling is mainly realized through regulating flow rate and direction in China, It is still not very convenient to adjust the water temperature. Moreover, it is basically separate for analysis, prediction, decision-making and feedback control on the water-supply scheme for each storehouse; the ideal temperature-control curve is also established for each storehouse separately without consideration of the dynamic temporal and spatial variation of temperature control in real time; the index system is still not sound and dedicated for the intelligent temperature control. There is still a lot of room to improve the intelligent water supply more scientific, refined and intelligent; (4) Besides the material, the component / structure is more essential for the anti-cracking of mass concrete structure; however, the analysis on this aspect is less yet at present; and (5) Now, it is still not timely for the feedback simulation & analysis on temperature control of dam tracking. The whole-dam tracking simulation is carried out once for Huangdeng Dam every three months; and once for Wudongde and Baihetan projects every month. It is possible to build a cloud monitoring platform for real-time whole-dam and whole-process performance simulation & feedback and safety evaluation for subsequent projects, so that simulation tracking analysis, evaluation and feedback can be more timely and precise [4].

3. Overall Architecture of Intelligent Temperature-control System

The intelligent temperature-control system for concrete dam is developed by the research group of China IWHR (Institute of Water Resources and Hydropower Research) over 15 years [5-10], which is used to prevent mass concrete from cracking. It integrates various systems (e.g.: AI technology, big data technology, IoT technology, information-mining technology, whole-dam whole-process simulation technology and automatic control technology) to realize the dynamic intelligent monitoring, analysis and control of temperature-control construction, including real-time collection and transmission, automatic management and evaluation of temperature-control information during construction, real-time early warning of cracking risk, intelligent temperature control and feedback of cracking risk, and simulation of temperature stress tracking and feedback [11], as well as criteria and measure optimization and so on. It is composed of the real-time collection and transmission, efficient management and visualization of information on construction and temperature control, effect evaluation and early warning of temperature-control construction, intelligent control of temperature-control construction, simulation analysis, tracking, feedback, prediction and evaluation on temperature stress and so on, which can realize such functions as intelligent control of poured concrete microclimate, intelligent water-cooling control, intelligent insulation early-warning and decision-making [12,13]. During the construction, it can timely track and optimize the temperature-control criteria and measures, and feed them back through the intelligent system, so as to realize the dynamic intelligent whole-process control and feedback for concrete dam from raw materials to mixing, transportation, pouring, temperature monitoring, water cooling, even protection and maintenance, and ensure the quality of dam construction under complex and serve conditions [14]. The system structure is shown in figure 1 below.

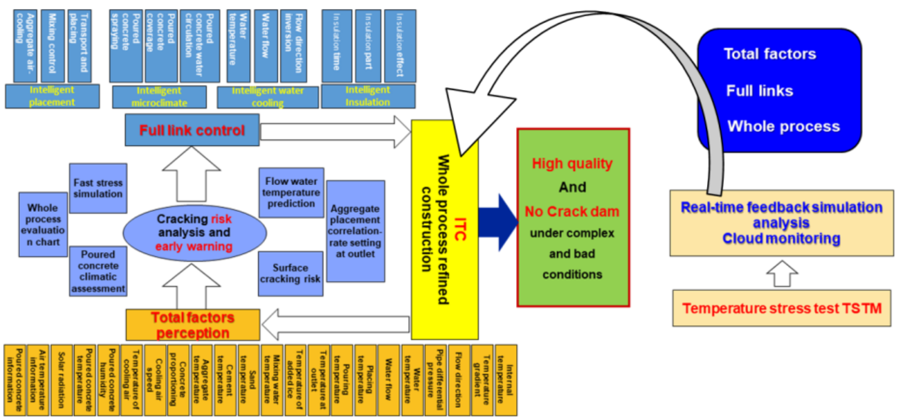
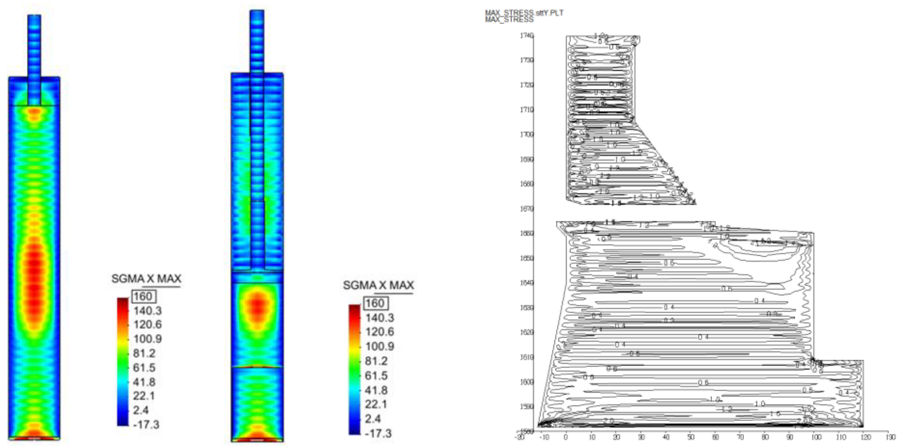


Figure 1. Functional structure of intelligent temperature-control system.

4. Research and Development of Key Technologies

4.1. Whole-Process and Whole-Dam Simulation & Analysis Method

The whole-dam and whole-process simulation & analysis is a fundamental method to study the real working behaviors of the dam, which has three basic characteristics: the first is to simulate the whole dam, including all transverse joints, angles, orifices, gate piers and complex geological conditions; the second is to simulate the whole process of working behaviors since the dam pouring from the first concrete storehouse, including the construction period, initial impoundment period and operation period; and the third is to simulate various aspects as close to the real state as possible, including the model, boundary conditions, construction process and calculation parameters [15], etc. In this field, the research team has carried out innovative researches in many aspects, such as rapid automatic dam modeling, substitution of the curtain of drainage holes by seeping layers for analysis on seepage field, model for simulating the real behaviors of transverse joints, efficient parallel algorithm for solving equations, method to determinate real parameters and criteria of concrete, etc., and formed the whole-process simulation & analysis method of concrete dam and SAPTIS simulation calculation program, which laid a foundation for studying the real working behaviors of concrete dams. It can display the spatiotemporal state and distribution of temperature and stress in various forms [16]. As shown in figure 2 for a typical expression of results. In addition, there are other expressions, such as process lines.



(a) Cloud chart of maximum transverse stress on upstream and downstream surfaces of typical dam section.

(b) Envelope line of maximum longitudinal stress in typical dam section.

Figure 2. Feedback analysis results of temperature and stress simulation.

4.2. Key Technologies to be developed for Intelligent Temperature-Control System

In view of the current status and insufficiency of intelligent temperature-control technology, the works below need to be carried out or further improved:

(1) **Intelligent outlet**: Since many technical issues still exist, including the intelligent digital control unavailable to the concrete production and mixing system; moreover, the evaluation, early warning and intelligent feedback control still absent for the outlet temperature, it is necessary to study the key technologies of intelligent mixing and real-time monitoring method of raw materials during concrete production and mixing, establish the predictive control model specific to the outlet temperature, and prepare the mixing scheme and optimal adjustment in real time. The outlet temperature-control model is used to dynamically adjust and control the pouring temperature with taking climate conditions, heat loss of transportation and pouring as constraints. Focusing on the compliance outlet temperature and the optimized cost, it is to dynamically optimize the injection temperature of each kind of raw material (aggregate, cement, fly ash, water, ice) (as shown in formula 1).

$$\begin{aligned} &\min p(T_i) = \min\left(\sum T_i G_i p_i + G_c p_c\right) \\ &s.t. \sum T_i G_i c_i = T_0\left(\sum G_i c_i\right) + k\eta G_c - Q \quad (1) \\ &T_i \in D, \quad i = 1, \ldots, N| \end{aligned}$$

(2) **Intelligent spraying**: For the Project located in the dry and hot valley facing intense radiation, it is necessary to develop the intelligent method specific to the poured concrete environment to control its temperature. We developed the relationship model between the external and internal poured concrete environments and the operating parameters of spray equipment. As shown in formula (2). According to this formula, the spray quantity of sprayer can be calculated according to the parameters of internal poured concrete temperature, measured air temperature and solar radiation.

$$\phi_{iw\max 01} = \left(AQ_{w\max} - B\right)\left[1 - e^{-C\left(\frac{V_{w\max}}{40D_r}\right)^D}\right] \tag{2}$$

(3) **Further research on intelligent water cooling**: Since the current intelligent water supply can't control the dynamic temporal and spatial temperature variations between poured concretes in real time, it is necessary to further study how to establish the index system of intelligent temperature control with consideration of the multi-dimensional and temporal distribution on the basis of the current research progresses of intelligent temperature control in some projects, such as Huangdeng Projects, research the corresponding intelligent water cooling control model and develop new intelligent water cooling module, so as to realize the water supply more scientific, fine and intelligent.

(4) **Intelligent thermal insulation**: In order to control construction measures during protection and maintenance, an early-warning model shall be developed to display temperature stress and inverse the cracking risk in real time, which can predict the variation of temperature stress on concrete surface through sensing the internal temperature of concrete, sudden drop of temperature, environmental temperature and temperature gradient; moreover, the evaluation model shall be established specific to surface insulation effect (e.g.: formula 4), so as to realize the early warning for the upstream and downstream surface and temporary poured concrete, and provide suggestions on part, thickness and materials of insulation.

$$K(t)=\frac{R(t)}{\sigma(t)}=\frac{R_0(1-e^{-\beta\tau})}{\Delta T(t)\dfrac{E(t)\alpha}{1-\mu}e^{-\frac{b}{G}}},\quad G=\frac{\partial T(t)}{\partial x} \tag{3}$$

$$\beta=\frac{\lambda\left.\dfrac{dT}{dx}\right|_{x=0}}{T_0-T_{a0}}=\frac{\lambda k_2}{T_0-T_{a0}} \tag{4}$$

4.3. Assessment on Cracking Risk of Concrete Dam and Optimization on Temperature-control Criteria on the Basis of TSTM

Based on the TSTM (temperature-stress testing machine), it is available to measure the parameters of mixed materials under the real temperature history and the temperature stress of concrete under any temperature history in the laboratory, so that the more accurate and detailed concrete characteristics can be obtained from the structural level. Combined with numerical simulation, it is possible to couple from the levels of experiment and simulation, and then optimize the temperature-dropping process and improve the temperature-control criteria, so as to lower the cracking risk of concrete dam during construction. Figures 3 and 4 show the data-coupling feedback process for simulation & calculation of concrete temperature stress under real service and test conditions, which can realize the measurement of actual crack resistance and criteria optimization. The optimization thinking method is shown in figure 5.

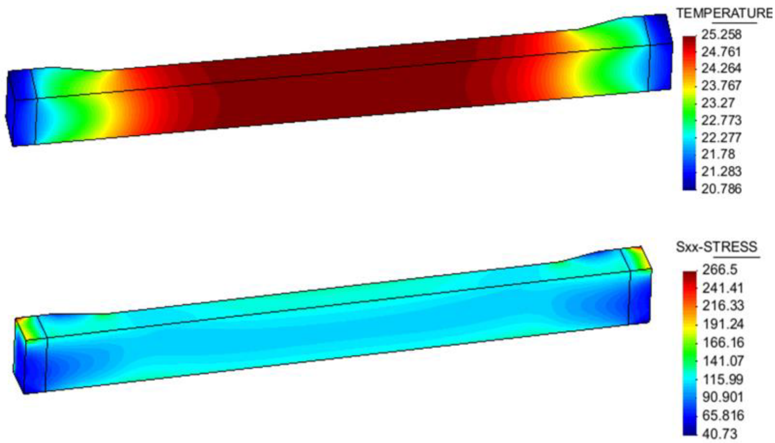


Figure 3. Cloud image of TSTM coupled feedback calculation results.

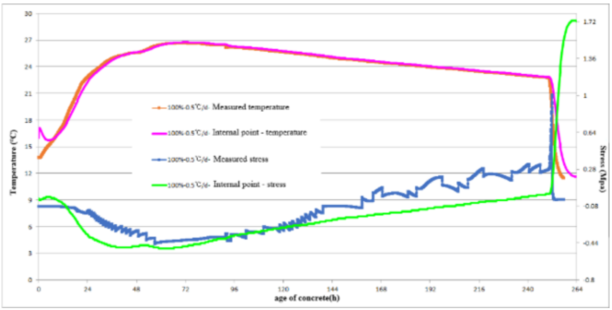


Figure 4. Coupling feedback results of TSTM and simulation calculation of real temperature stress.

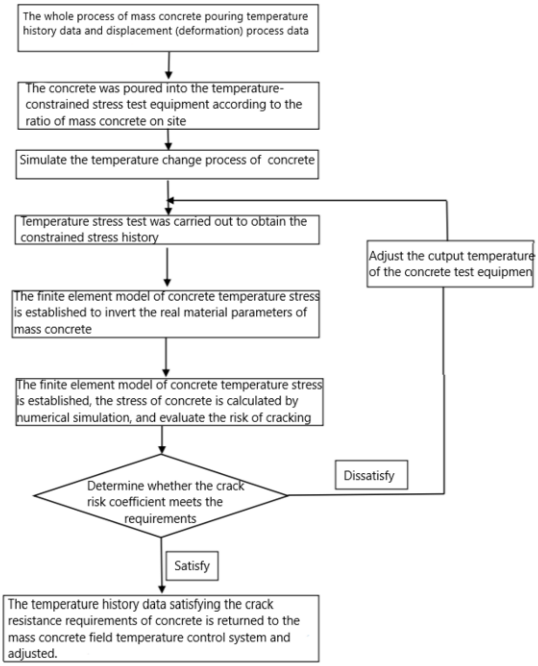


Figure 5. Optimization idea of crack prevention design based on temperature stress experiment.

4.4. Real-time Cloud Simulation & Monitoring Technology and Optimization of Intelligent Whole-Dam & Whole-Process Temperature-control Criteria

Based on the tracking simulation technology of Huangdeng, Wudongde and Baihetan projects, the cloud monitoring technology for the whole-process & real-time simulation and forecast of RCC dam can be established on the basis of big data analysis and cloud computation. Relying on SAPTIS platform, the cloud monitoring platform can be built for whole-process & real-time performance simulation & feedback and safety evaluation on the whole dam, so that the simulation, tracking analysis and feedback will be more timely and refined.

With the data and cloud computing platform of intelligent temperature-control system, as well as TSTM experiment, the tracking feedback, simulation and analysis on temperature stress can be carried out according to the measured data and site needs.

According to the actual construction situations, the weekly, monthly, annual and periodic simulation & analysis reports of temperature control can be put forward timely, so as to grasp the actual thermodynamic parameters and temperature stress state of dam concrete, evaluate the current situations and forecast the future, timely identify problems and propose solutions, track and optimize temperature-control criteria and measures, and feed back to the intelligent temperature-control system and site temperature-control construction, so as to form a new optimization method for intelligent temperature control. Figure 6 shows the cloud computing platform and calculation results by this method.

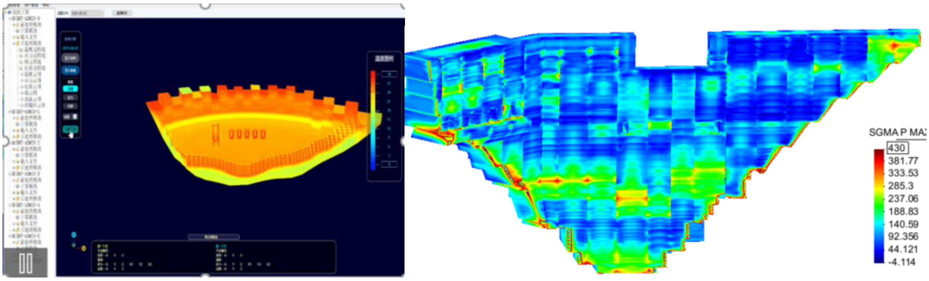


Figure 6. Cloud computing results for tracking & feedback of temperature stress for the whole dam.

5. Conclusions

Based on the intelligent temperature control in Huangdeng and Baihetan projects, we innovatively carried out a study on the intelligent whole-process temperature control (intelligent outlet, poured concrete, water supply and protection) during the construction of RCC dam in combination with the actual situations of projects in southwest China and current research progresses. This study will achieve the dynamic intelligent temperature control of whole time-space correlation during RCC dam construction, which can promote the intelligent monitoring indicators more comprehensive, systematic and scientific; realize the intelligent early warning and feedback guidance of the mixing system; establish the cloud monitoring technology and platform for real-time whole-dam and whole-process simulation and data integration analysis. The above researches promote the intelligent temperature-control technology to be more comprehensive, precise and scientific, which enriches the theory and method system of intelligent temperature control, and leads this field in China. The extension and application of following application will further enhance the management level and engineering quality of hydropower project construction, effectively prevent or lower cracking risk, provide favorable guarantee for water storage and power generation of the project, and provide more comprehensive data for safety appraisal, acceptance and operation management of the dam project.

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References

[1] Zhang GX. Development and application of SAPTIS - Software of multi-field simulation and nonlinear analysis structures (Part I). Water Conservancy and Hydropower Technology. 2013;44(1): 31-35

[2] Zhu BF. Temperature stress and temperature control of mass concrete (2nd Edition). China Water Resources and Hydropower Press. 1999

[3] Zhang L, Zhang GX. Development and application of SAPTIS - Software of multi-field simulation and nonlinear analysis structures (Part III). Water Conservancy and Hydropower Technology. 2014; 45(1): 29-33

[4] Liu Y, Zhang GX. Discussions on temperature control and crack prevention of concrete dam. Water Conservancy and Hydropower Technology. 2014; 45(1): 77-89

[5] Zhu BF, Zhang GX, Xu P, et al. Decision-supporting system for temperature and stress control during construction of high concrete dam. Journal of Water Resources. 2008; 39(1): 1-6

[6] Zhu BF. Digital monitoring of concrete dam. Water Conservancy and Hydropower Technology. 2008; 39(2): 15-18

[7] Zhu BF, Zhang GX, Jia JS, et al. Digital monitoring of concrete dam: A new approach to improve dam monitoring level. Journal of Hydropower Generation. 2009; 28(1): 130-136

[8] Liu Y, Zhang GX, Wang JM, et al. Digital monitoring method, system and engineering application during construction of super-high arch dam. Water Conservancy and Hydropower Technology. 2012; 43(3): 33-37

[9] Ma HQ, Zhong DH, Zhang ZL, Sun YJ, Liu DH. Key technologies for real-time control of major water conservancy and hydropower projects and their engineering applications. China Engineering Science. 2011; 13(12): 20-27

[10] Zhang GX, Liu YZ, Liu Y. The transition from "digital dam" to "intelligent dam" - research progress on temperature control and crack prevention of high dams. Technical Progresses in Reservoir Dam Construction and Management - Proceedings of 2012 Annual Meeting of China Dam Association. Zhengzhou: The Yellow River Water Resources Press. 2012; p. 74-84

[11] Zhang GX, Zhang L, Liu Y, et al. Inverse simulation and analysis on working behaviors of jinping i arch dam during construction. Key Technical Problems and Major Progresses of Hydropower Development in the Basin. Zhengzhou: The Yellow River Water Conservancy Press, 2014; p. 225-231

[12] Zhang L, Liu Y, Li BQ, Zhang GX, Zhang ST. Study on real-time simulation analysis and inverse analysis system for temperature and stress of concrete dam. Mathematical Problems in Engineering. 2015; Doi:10.1155/2015/306165

[13] Zhang GX, Liu Y, Li SH, Zhu BF. Researches and practices of "931" temperature control mode. Journal of Hydropower Generation. 2014; 33(2): 179-184.

[14] Zhang GX, Liu Y, Liu YZ, Li SH, Zhang L. Research progresses on temperature control and crack prevention of high concrete dam. Journal of Water Resources. 49(9): 1068-10782018

[15] Shi NN et al. Crack risk evaluation of early age concrete based on the distributed optical fiber temperature sensing. Advances in Materials Science and Engineering. 2016; 2016: 1-13.

[16] Zhao YQ, et al. Effect of Thermal parameters on hydration heat temperature and thermal stress of mass concrete. Advances in Materials Science and Engineering. 2021.