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Thermal anti-cracking safety control for concrete dams

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Abstract: Thermal cracking is an inevitable phenomenon in concrete dam construction. In this study, we develop a set of control technologies for concrete dam construction that mitigates thermal cracking. The key technological innovations include: (1) material production technology that improves the crack resistance of hydraulic concrete; (2) progress-temperature-behavior coupling control with the time interval as the key variable; (3) spatiotemporal temperature closed-loop intelligent control with pipe cooling as the core; (4) thermal anti-cracking safety systematic control based on five factors (homogeneity, continuity, proportionality, integrity, and durability; HCPID); (5) an intelligent construction management and control platform based on dynamic perception, analysis, and control. A comprehensive technical system for thermal anti-cracking safety control in concrete dams is established, with concrete quality functioning as the basis, construction process as the timeline, temperature control technology as the core driver, and the intelligent management and control platform functioning as a tool. The developed technologies were implemented in construction of the Xiluodu, Wudongde, and Baihetan concrete dams in China. Subsequently, thermal cracking was not observed in post-construction investigations. Our results provide a reference for design and construction for similar projects.

Key words: Concrete dam; Thermal anti-cracking safety; Intelligent cooling control; Hydraulic concrete

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1 Introduction

Thermal cracking of concrete accompanies the application of hydrating cementitious materials in dams (Adek and Anita, 2019). Concrete is a brittle and inhomogeneous material with low thermal conductivity. Moreover, its tensile strength is 1/10–1/14 of its compressive strength. Considering limitations such as construction capacity, pouring block size, poor heat dissipation, rapid increases in internal temperature, complex construction processes, hostile construction and operation environments, and others, thermal cracking in concrete comprising hydraulic structures is a difficult problem to address (Zhu, 2012). In the context of concrete dams, cracks reduce the effective section area and the bearing capacity, thus reducing safety. Cracks also cause concrete corrosion, reduce concrete durability, and shorten the working life of dams (Wang and Maekawa, 2022; Wang et al., 2023). At the same time, cracks destroy the integrity of structures and treating them increases project costs. In addition, temperature and humidity usually affect concrete performance in tandem, which is particularly relevant for dams (Sun et al., 2023). Under the action of a high water head, cracks may develop into a seepage channel or even propagate into the structure, severely affecting the long-term safety of dams. And as hydropower development expands to high-altitude regions, cracks will also be affected by freeze-thaw cycles, further endangering dam structures (Gong et al., 2023).

Thermal cracking in concrete dams is a challenge in terms of design, construction, and operation (Zhu, 2006; Zheng, 2009; Zhang et al., 2018). For example, Jiari (built in 1953, France), Tuola (built in 1960, France) and Kolnbrein (built in 1978, Austria) have all had to be reconstructed, repaired, or reinforced because of severe thermal cracking following

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reservoir impoundment (Zhu, 2006; Yang et al., 2010; Jia, 2016). In 1985, the Sayano-Shushenskaya arch dam in Russia was observed to have 5,590 cracks, existing in 24% of the concrete blocks (Wang, 2009). In the 1980s, the breakthrough of 7°C precooling concrete in the concrete mixing system of the Gezhouba hydropower station (Xie, 1983), as well as the treatment of concrete cracks in the constrained foundation of the Dongjiang arch dam, improved concrete temperature control technology for dam engineering in China (Peng and Lin, 1987). By optimizing temperature control measures in the Three Gorges project, localized surficial cracks in the flood discharge dam sections constructed in the second phase were treated, and surficial thermal cracking in the third phase was minimized (Zheng, 2009). Surficial cracks were observed in the Ertan arch dam (completed in 2000) during construction and operation (Yang et al., 2010). The Xiaowan arch dam began to pour at the end of 2005, and internal cracks parallel to the dam axis were observed in certain dam sections in October 2007 (Wang et al., 2011). Later in March of 2008, a large range of penetrating cracks were observed in the unconstrained region during joint grouting (Wang, 2009). In addition, during the construction of Laxiwa, Jinping I, Goupitan, and other arch dams, concrete has experienced cracking of various degrees (Wang, 2009; Tang and Zhang, 2011; Li, 2013). Note that these dams have been carefully inspected and treated and are under continuous monitoring; thus, they still operate safely and effectively.

2 Development history of thermal anti-cracking safety control for concrete dams

The construction of concrete dams without thermal cracks is a major goal for hydraulic engineers. Since 2000, construction of 300-m-level concrete arch dams in Southwest China has expanded (Jia, 2016; Fan, 2017; Fan et al., 2022). With high reservoir water pressures, high stress in the dam concrete, high strength grades required for the concrete, large amounts of cement consumed in construction, and high adiabatic increases in temperature due to hydration exothermic reaction, 300-m-level arch dams necessitate high standards for concrete thermal cracking control. Because of the influence of structure shape, material properties, construction practices, and other factors, characteristics emerge which present challenges for thermal cracking control in high arch dams. These include the larger bottom width and larger length-to-width ratio of concrete blocks, the increase in internal temperature after pipe cooling of medium-heat cement concrete mixed with fly ash and a high content of magnesium oxide, and the rapid cooling prior to joint grouting with a low arch closure temperature.

To remediate thermal cracking, researchers have continuously made improvements in temperature control theory, concrete materials, intelligent cooling control technologies, and other aspects through innovative approaches. Significant breakthroughs have been achieved in terms of thermal anti-cracking control for mass concrete design and construction. These improvements are outlined in Fig. 1:

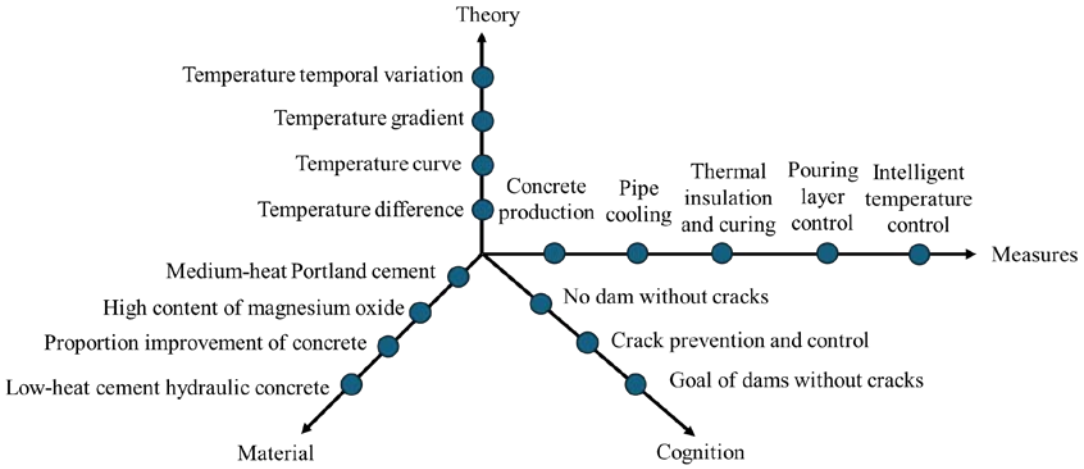

Fig. 1 History of dam thermal anti-cracking safety control

(1) Theories: Temperature control theories have been developed based on structural analysis, experi-

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mental research, and feedback monitoring; some examples include prevention of penetrating cracks in foundations by controlling the highest temperature to reduce the temperature difference (Peng and Lin, 1987), prevention of surface cracks by external thermal insulation, and curing to tackle changes in ambient temperature (Zhu, 2006). With the application of technologies such as intelligent cooling, more precise temperature control theories are being developed, with many leveraging temperature curves, gradients, and temporal variations (Lin et al., 2013; Zhang et al., 2018; Ning, 2022).

(2) Materials: In Fan et al. (2016a), a medium-heat Portland cement with a high content of magnesium oxide was developed for the Xiluodu dam. The thermal and mechanical performance of the concrete was improved through analysis of the temperature control mechanism and experimentation with the proportions of fly ash admixture, high-efficiency admixture, polyvinyl alcohol (PVA) fiber, silica fume, and other materials (Fan et al., 2016a). Based on practical examples of the Hoover, Three Gorges, Xiangjiaba, Xiluodu, and other dams, technical standards for low-heat cement suitable for hydraulic concrete have been formulated (Wang et al., 2018a; GB/T 200). Low-heat cement hydraulic concrete with improved crack resistance has accordingly been developed (Fan et al., 2016b) and applied to the Wudongde and Baihetan superhigh arch dams with good results (Li et al., 2017).

(3) Construction measures: During the Gezhouba project in China, the target control of an out-of-mixer temperature of 7°C was achieved via different technological innovations, such as adding water-cooled aggregates and concrete mixing by adding ice or cold water (Xie, 1983). During the construction of the Three Gorges project, water-cooled aggregates were replaced by air-cooled aggregates in laboratory tests and production trials, and have been widely applied thereafter (Niu, 2022). Cooling pipes have also been widely utilized in

concrete dam construction (Adek and Anita, 2019). The long-term effect of surface thermal insulation has been investigated and tested in dam projects such as the Three Gorges, Xiluodu, and others. The method and technology have been constantly improved to strengthen targeted surface thermal insulation during cold waves or seasons for long-term thermal insulation and curing (Zhu, 2006; Zhang et al., 2018). In terms of the pouring layer thickness control, 1.5- and 3-m lift technologies for large block surface pouring were developed for the Three Gorges, Ertan, and other projects. Furthermore, a greater lift thickness pouring technology of 4.5 m was applied in the Jinping I, Wudongde, and other dams (Wang et al., 2015), providing a possible solution for the conflict between temperature control and rapid pouring.

The collection and analysis of temperature control information directly determines the scientificity, intelligence, and effectiveness of thermal cracking control (Zhong et al., 2011; Lin et al., 2013). Numerical simulation has laid a foundation for improved evaluation of thermal anti-cracking safety and control strategies (Fu et al., 2011; Zhang et al., 2018). Simultaneously, the development of information technologies, such as data mining and artificial intelligence, has provided favorable conditions for intelligent temperature control methods to blossom. Upon the application of customized pipe cooling in the Three Gorges Dam (Zheng, 2009; Niu, 2022), a new intelligent cooling control technology (Lin et al., 2013) was successfully applied in the Xiluodu, Wudongde, Baihetan, and other projects (Ning et al., 2022). This significantly improved the quality and efficiency of temperature control, essentially providing an approach to control thermal cracking.

(4) Thermal anti-cracking cognition: With the continuous evolution of dam construction technology and practice, the cognition of thermal cracking control has evolved from no dam without cracks (Zhu, 2006), to crack prevention and control (Zhang et al., 2018), to dams without significant cracks (Zhang et al., 2010; Fan et al., 2021). A dam without significant cracks has been built as a reality (Yang and Song, 2021). On June 1, 2021, Chinese People's Daily newspaper reported: "On the mainstream of the Jinsha River, the Baihetan hydropower station, which is currently the largest dam under construction in the world with a total installed capacity of 16000 MW, was poured to the top in the afternoon of May 31, 2021. No thermal cracking has occurred since the first pouring, indicating that China has fully mastered the technology of thermal cracking control for mass concrete." From the practice of thermal cracking control in Baihetan and other projects on the Jinsha River, it has been revealed that a key to mitigating

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thermal cracking is to understand the real crack resistance of concrete in the entire construction process; moreover, it is important to conduct evaluations and develop effective and innovative control strategies.

3 Novel technologies for thermal anti-cracking safety control in concrete dams

A key to anti-cracking safety control in concrete dams is the relationship between the real crack resistance of the concrete and the real spatiotemporal stress level of the structure. Through full life-span control of concrete temperature, structural stress in concrete, crack resistance, and technological innovations regarding thermal cracking by utilization of intelligent construction closed-loop control theory (Fan et al., 2021), thermal cracking problem can be effectively solved.

Based on the construction practice of Xiluodu, Wudongde, Baihetan, and other 300-m-level arch dams, in this study we summarize the successful experiences and theoretical system that was developed for anti-cracking safety control in concrete dams. By accounting for the temporospatial evolution of and relationships between concrete temperature, construction progress, concrete strength, concrete stress, deformation, and anti-cracking safety, the comprehensive anti-cracking control method and technical system were designed accordingly. It has structural safety as its premise, concrete quality as its basis, progress as its thread, resources as its guarantee, and intelligent closed-loop control of temperature as its core driver, and these aspects are investigated as such. Our findings provide a reference for the development and application of anti-cracking safety control systems in future concrete dams.

3.1 Material production technology for improving crack resistance of hydraulic concrete

(1) Technical method of thermal anti-cracking control for 300-m-class super-high arch dams

The Xiluodu arch dam features coarse basalt and fine limestone aggregates. To prevent the thermal cracking of concrete, advanced thermal anti-cracking control technology and heavy management measures were adopted, including (i) usage of medium heat cement with high magnesium oxide content so as to reduce the volume shrinkage deformation of the concrete; (ii) basic requirements for the pouring of precooling concrete throughout the year, pipe cooling for dam concrete in the entire process, and thermal insulation and curing throughout the year; and (iii) an intelligent cooling control system with responsible implementation of the technology and thermal anti-cracking measures for the concrete.

Owing to challenges in the construction of the Baihetan and Wudongde arch dams – namely the dam shapes and adverse weather conditions including strong winds, dryness, and heat – to improve the safety and reliability of thermal anti-cracking control, artificial limestone aggregates are selected and the innovative thermal anti-cracking control technologies of the Xiluodu dam were applied. intelligent cooling control system and low-heat cement concrete were fully applied, and a concrete dam without significant thermal cracks had been built. Thus, a comprehensive technical system was formed with core temperature control technologies, such as the combination of "medium heat cement/low heat cement + precooling concrete + first-class fly ash + efficient admixture + intelligent cooling system + fully covered curing and insulation."

Table S1 lists the main technical parameters of the medium- and low-heat cement used in the Xiluodu, Wudongde, and Baihetan dams. In the engineering practice, two hydraulic concrete technical routes represented by medium- and low-heat cement were formed, which can both meet the target thermal anti-cracking control requirements of the hydraulic concrete. However, on the contrary, the use of low-heat cement hydraulic concrete can better achieve the goals of a controllable highest temperature, an adjustable temperature change process, and optimizable temperature control measures. Low-heat cement has become an alternative solution for construction of mass concrete. For example, the latest Chinese industry standard, Concrete Arch Dam Design Standard (NBT/10870), notes that high dams should use medium- or low-heat Portland cement.

(2) Production of medium-heat cement with high internal magnesium oxide content

Based on a comprehensive comparison of the two technical paths of medium-heat cement mixed with magnesium oxide and high internal magnesium oxide, along with leveraging engineering research, process analysis, and material tests, the second tech-

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nical path of medium-heat cement with high internal magnesium oxide was adopted in Xiluodu, and the micro shrinkage of concrete was controlled within 20 micro strains. The Xiluodu project proposed the medium-heat cement production method of "two grinding and one burning" for their high arch dam (Fan et al., 2016a). First, the design values of the lime saturation factor (LSF), silica modulus (SM) (= SiO_2 / (Al_2O_3 + Fe_2O_3)), and alumina modulus (IM) (= Al_2O_3 / Fe_2O_3) ratios of cement raw materials are defined. Limestone, shale, sandstone, dolomite, and zinc slag were used as raw materials to obtain the mixture, and coal (calorific value > 5500 kcal/kg) was selected as the burning fuel. Second, the mixture was ground to obtain cement raw meal. The actual three-ratio value of the cement raw meal was tested, and the raw material ratio was adjusted accordingly to ensure that it fulfilled the design requirements. Third, the cement raw meal was calcined in a kiln to obtain a cement clinker. The lime saturation factor (LSF), SM (=SiO_2/(Al_2O_3+Fe_2O_3)) and IM (=Fe_2O_3/Al_2O_3) ratios of the cement raw meal in the kiln were controlled, and the calcination was conducted to partial melting at the calciner outlet temperature range of 860–930°C and the kiln hood temperature range of 1000–1150°C, forming a clinker with the main minerals of C_3S, C_2S, C_3A, and C_4AF whose weight exceeded 1200 g/L. Note that in this process, the clinker must be uniformly granulated, the minerals must be completely developed, and no reduction atmosphere should be used. Finally, the cement clinker was ground with gypsum to obtain the finished cement product. The cement clinker and natural dihydrate gypsum with crystal water content > 15% and SO_3 content > 38% were added to the cement mill at reasonable proportions for mixing and grinding (such that the SO_3 content in the milled cement was < 3%, the specific surface area was ≤ 330 m^2/kg, and the water mud temperature was < 110°C.

(3) Production of low-heat cement concrete for 300-m-level super-high arch dams

The thermal anti-cracking control method for the mass hydraulic concrete of super-high arch dams based on low-heat cement concrete (Fan et al., 2016b) was adopted in the Baihetan and Wudongde dams. The purpose of this method is to limit the temperature change and shrinkage of hydraulic concrete and prevent thermal cracking by controlling the material composition of hydraulic concrete and the pouring process. The method specifically involves precooling aggregate and adding flake ice and cold water to control the out-of-mixer and pouring temperatures of hydraulic concrete; using low-heat cement and adding high-grade I fly ash as the cementitious material; embedding cooling pipes to control the highest temperature of the hydraulic concrete; utilizing four-grade aggregates and PVA fibers to prevent cracks; controlling the out-of-mixer temperature of the hydraulic concrete to ≤ 7°C in the summer and ≤ 9°C in the winter; controlling the pouring temperature to ≤ 12°C and the highest temperature to ≤ 27°C. In the concrete mix proportion, the content of Grade I fly ash is 35%, and the water-reducing agent and air-entraining agent are prepared on-site in a solution with mass concentrations of 20% and 1%, respectively. The length of the PVA fiber is within 12–15 mm, with an equivalent diameter in the range of 14–20 μm, a breaking strength ≥ 1500 MPa, and a mixing amount of 0.9 kg/m^3. The temperature ranges of the flake ice and cold water used are −7°C to −5°C and 5 to 7°C, respectively, and the temperature of the four-grade aggregates is controlled to the range of −2 to 1°C by air cooling.

Table 1 presents a comparison between mineral composition, thermodynamic properties, etc. of medium- and low-heat Portland cement concrete. Based on the long-term crack resistance test results of medium- and low-heat cement concrete, which use the actual mixing ratio as in the project under laboratory and on-site conditions, a basic understanding of the real crack resistance was formed. Specifically: (i) The hydration heat and adiabatic temperature increase in low-heat cement are lower at each age than those of medium-heat cement (Figs. 2a and 2b). The hydration reaction and exothermic rates of low-heat cement are relatively slow, which can better perform pipe cooling and other measures to control the spatiotemporal temperature gradient. (ii) Low-heat cement exhibits low early strength and high late strength rates of increase. Generally, after 60–90 days of age, its tensile and compressive strength exceeds that of medium-heat cement (Fig. 2c). (iii) Low-heat cement concrete possesses characteristics of large ultimate tensile strain, good impact, wear resistance, and more dense hydration products.

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Table 1 Property comparison of low- and medium-heat Portland cement concrete materials

Properties	Low-heat cement concrete (LHC)	Medium-heat cement concrete (MHC)
Mineral composition (Li et al., 2017)	Mainly C_2S with low hydration in the early stage and continuous hydration in the later stage.	Mainly C_3S with high early hydration, early high strength, and fast hardening.
Chemical reaction (Ji, 2010)	$2C_2S+5H_2O=C_3S_2H_4+Ca(OH)_2$ △H=-43KJ/mol	$C_3S+7H_2O=C_3S_2H_4+3Ca(OH)_2$ △H=-118.4KJ/mol
Heat of hydration	The hydration heat of LHC is lower than that of MHC at each age, with an average difference of 50KJ/Kg.	
Adiabatic temperature rise	The adiabatic temperature rise of LHC is lower than that of MHC at each age, with a difference of 2.0~3.5 ℃ in 28d (Fan et al., 2018) and a maximum difference of 4.8℃ (Chen et al., 2021).	
Strength	The strength of LHC is lower than that of MHC at an early age (7d, 28d), and is generally higher than MHC after 60~180d (Fan et al., 2018; Chen et al., 2021).	
Elastic modulus	The law is similar to strength.	
Ultimate tensile strain	The law is similar to strength.	
Autogenous volume deformation	The autogenous volume deformation of LHC is close to MHC, both of which are dominated by micro expansion (Fan et al., 2018), related to water binder ratio and MgO content.	
Creep	The creep of LHC is close to MHC.	
Shrinkage	The shrinkage of LHC is slightly lower than MHC (Chen et al., 2021).	
Durability	The pores are relatively few in LHC, and the calcium silicate gel of LHC is more compact (Chen et al., 2021).	
Crack resistance test	Plate method test: the cracks formed in LHC are thin, the initial crack time is delayed, and the number of cracks and the average crack area are small (Ji, 2010); Ring temperature fracture test: the crack width of LHC is much smaller than MHC (Shi et al., 2015).	

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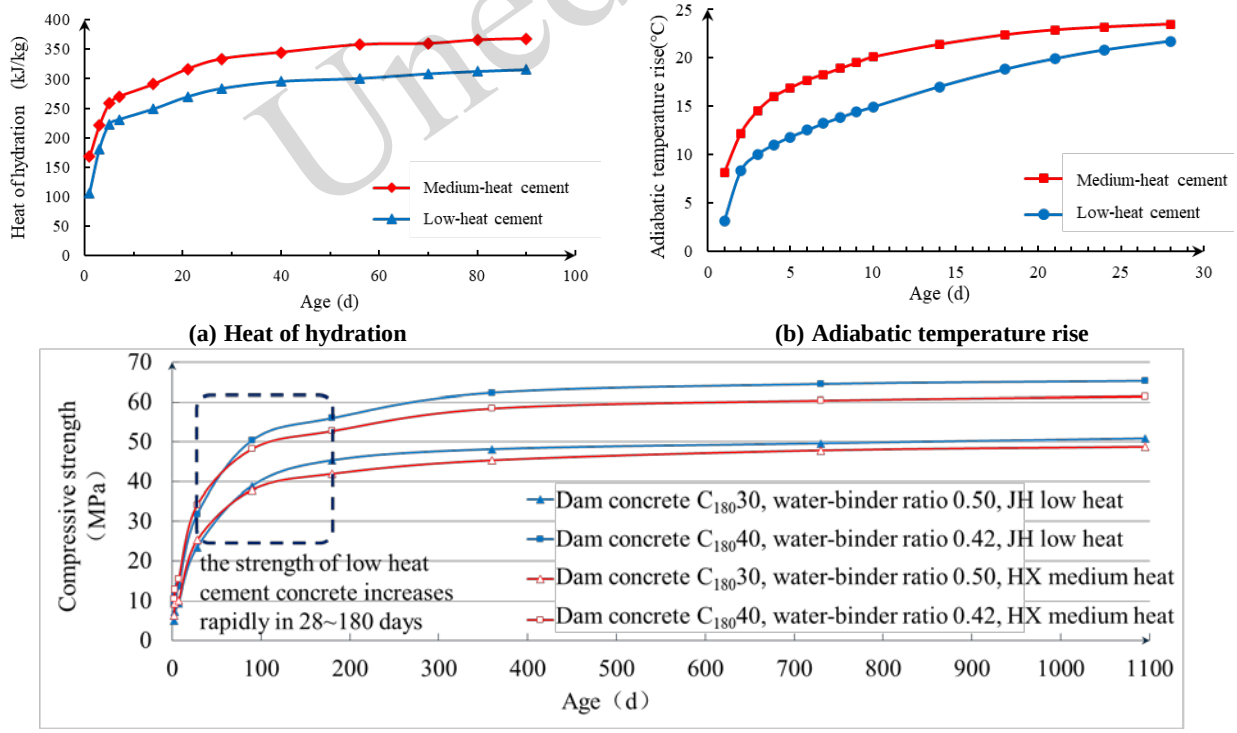

(a) Heat of hydration **(b) Adiabatic temperature rise**

(c) Compressive strength (Fan et al., 2018)

Fig. 2 Comparison of thermodynamic properties development of medium- and low-heat cement concrete

3.2 Progress-temperature-behavior coupling control with pouring interval as a key variable

The progress of dam construction directly determines the thermal and structural stresses in dam concrete, which are closely related to structural safety. It is crucial to have structural safety as the main goal, and consider the preprocessing of foundation treat-

ment, construction resource constraints, temperature control status, etc., in conducting real-time coupling analysis and dynamic adjustment. Foundation treatment is the preprocess of concrete pouring, whereas concrete pouring is the preprocess of pipe cooling, joint grouting, etc. Foundation treatment affects the pouring progress. Once the pouring progress changes, the corresponding temperature control and joint grouting scheme changes. The long interval caused by the pouring lag increases the constraint of old concrete on newly poured concrete, thereby increasing the risk of structural cracking. However, it will also cause the cantilever height, maximum height difference, and adjacent height difference to be uncontrollable because of the joint grouting delay, which is unfavorable to the control of dam proportionality and continuity.

(1) Consolidation grouting technology with no covering weight

To construct concrete in a dam foundation-constrained area, the key points of thermal anti-cracking control are to select the appropriate pouring season, such as the low-temperature season, and to shorten the occupation time for the dam concrete pouring through dam foundation consolidation grouting. Under the condition that the concrete in the foundation-constrained region of arch dams must be poured year round, dam foundation consolidation grouting technology introduces benefits of rapid and continuous concrete construction, and also prevents concrete cracking in the strongly constrained region. Thus, based on the technical measures of the primary excavation of bedrock and the secondary construction of bedrock consolidation grouting in the bank slope dam section (which does not occupy the dam concrete pouring block surface), a consolidation grouting method with no covering weight or with bedrock covering weight is developed for the riverbed dam section. For example, based on the revealed geological conditions of the dam foundation, consolidation grouting with no covering weight and secondary pipe-guide high-pressure regrouting were adopted at the Wudongde dam. For the Baihetan dam, foundation consolidation grouting with a protective layer weight was conducted where the protective layer was to be excavated for the riverbed dam foundation. Based on the grouting effect test, the secondary grouting for the shallow rock mass after excavation of the protective layer was conducted using the effective weight after the dam height increased through the guide pipe in the dam. The dam foundation consolidation grouting effect for columnar jointed basalt and breccia lava was improved with an increase in grouting pressure. This reduces the impact on subsequent concrete pouring and ensures an efficient transition with continuous operations from foundation treatment to concrete pouring (Chen et al., 2021).

(2) Progress-temperature-behavior coupling control technology

The construction progress of concrete dams directly affects the evolution of temperature fields and the structural safety. Therefore, this problem must be addressed in a related manner (Wang et al., 2018b; Guan et al., 2018). During the concrete pouring stage, to enable spatiotemporal evolution process control of concrete anti-cracking safety measures (with temperature control as the core driver), the concrete pouring progress should be controlled based on analysis of the pouring progress and the interlayer interval control method (Fig. 3a). The general process is as follows: (i) Based on analysis of real working behavior, the initial minimum interlayer interval t0 is established. (ii) Based on the initial minimum interlayer interval t0, considering the boundary conditions, equipment resources, and production efficiency that restrict the pouring progress, the construction progress simulation analysis is conducted. The construction schedule plan with t1 as the preset interlayer interval is referred to as the preset plan. (iii) The temperature control and joint grouting process of the dam are deduced based on this preset plan. Accordingly, simulation analysis of the working behavior is performed considering the real parameters, loads, and boundary conditions of the dam, and feedback is provided if the preset plan fulfills the anti-cracking safety requirements. If not, the scheduling scheme is reoptimized until the scheduling scheme and the corresponding temperature control and grouting schemes meet the requirements. If the requirements are met, the preset interlayer interval time t1 is determined as the optimized planning interval t2. (iv) Construction organization is performed based on the planning interval t2, the corresponding human and equipment resources are allocated for actual construction, and the real interlayer interval t3 is obtained; and (v) The actual interval t3 and planning interval t2

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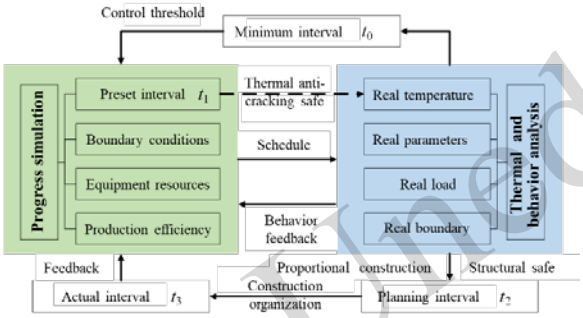
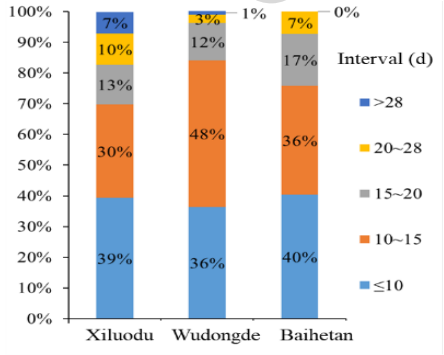
are compared. Should the actual interval deviate from the planning interval, a new optimization cycle is started.

Effective progress-temperature-behavior coupling analysis with pouring interval as the key control factor can significantly improve the efficiency of dam pouring. For example, the design requirement for the interlayer interval of the Xiluodu dam is 5–28 days, that of the Baihetan dam is normally 5–7 days, and the maximum is not allowed to exceed 20 days. The interlayer interval can be minimized on the premise of meeting the minimum value. Fig. 3b shows the actual interlayer intervals of Xiluodu, Wudongde, and Baihetan. The coincidence rates of the interlayer intervals within 15 days are 69%, 84%, and 76%, and those within 28 days are 93%, 99%, and 100%, respectively.



(a) Control method



(b) Application effect

Fig. 3 Progress analysis and control method based on the interlayer interval and its application effect

3.3 Intelligent closed-loop temperature control technology with pipe cooling as the core driver

The comprehensive measures for the thermal anti-cracking control of 300-m-level superhigh arch dam concrete include strict temperature control standards that consider constraints for the entire dam, the pouring of precooling concrete, pipe cooling for dam concrete, thermal insulation and curing, and joint grouting, all throughout the year. Following the intelligent closed-loop control principle of "comprehensive perception, real analysis, real-time control, and continuous optimization," a control system was built for the mixing, transportation, pouring, pipe cooling, thermal insulation, and curing processes (Fig. 4), in order to control the concrete temperature process curve.

(1) Intelligent cooling technology as the core measure of thermal anti-cracking control

The key to concrete temperature control is the multidimensional temperature gradient of the dam body, and the core driver of this method is pipe cooling following determination of the materials, structures, and environment. The various control requirements at each stage, such as the target temperature, drop amplitude, change rate, water temperature, and flow rate, need to be guaranteed by the accurate cooling process control in real time; this cannot be realized by traditional manual pipe cooling methods, which have low feedback speed. Novel intelligent cooling control technology can ensure reasonable and manageable distribution of thermal stress and prevent cracking (Lin et al., 2013; An et al., 2024).

The proposed intelligent cooling technology uses a digital thermometer, distributed optical fiber, and other components to monitor the spatiotemporal temperature evolution process of concrete in real time (Peng et al., 2020). This technology uses integrated intelligent cooling control equipment to monitor the temperature and flow of the cooling water in real time; analyzes the temperature distribution, gradient, and change rate in the concrete; and forms a real three-dimensional temperature field (Lin et al., 2021). It calculates the real thermal stress and cracking risk, forms a continuous and optimized temperature control strategy, intelligently manages the operational status of the valves and water supply equipment, etc., and enables on-demand intelligent control of the temperature, flow, and direction of cooling water (Ning, 2022).

Research on the theories and methods of intelligent temperature control has revealed that, due to the low heat and slow heat characteristics of concrete, continuous pipe cooling modes, and controllable water temperature, a continuous and stable cooling control strategy with dynamic optimization of curve

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segmentation should be adopted. Optimization of the target temperature control curve can be performed by minimizing the thermal stress or temperature gradient (Ning, 2022).

(2) Intelligent temperature control of concrete during mixing, transportation, and pouring

Based on infrared or online temperature sensing technology, the aggregate, out-of-mixer, placing, and pouring temperatures can be measured. Through the intelligent analysis and control of concrete construction, including mixing production, horizontal transportation, vertical transportation, and block surface operation, the out-of-mixer, placing, and pouring temperatures at different parts and in different seasons can be controlled in a stable manner. Thus, accurate temperature control of mixing, transportation, and pouring can be realized, with reductions in energy waste and pollutant emissions.

(3) Environmental control on the block surface and in the gallery

By establishing small integrated weather stations onsite, environmental data on the block surface and in the gallery are monitored in real time, such as temperature, humidity, wind speed, and solar radiation. Based on this monitoring data, the spatial distribution of temperature and humidity can be analyzed dynamically, and the direction, temperature, flow, and other working state parameters of the spray or humidifier can be controlled according to the temperature control strategy and requirements; in this way, one can control the local environment on the block surface and in the gallery (Yang et al., 2021). Regarding the pouring surface of the concrete block, a local environment suitable for concrete pouring is formed to prevent an increase in concrete temperature due to the ambient temperature. For the gallery in the dam, local surface cracks due to inadequate curing and windproof measures should be prevented.

(4) Intelligent control technology for fully covered thermal insulation and curing

Many engineering tests and analyses have shown that long-term thermal insulation on the permanent surface of a dam, timely thermal insulation on the concrete working surface, and an exposed surface during construction are indispensable. Requirements for technical indicators of thermal insulation materials are proposed with these facts in mind. For example, customized and fully covered thermal insulation on upstream and downstream surfaces, transverse joint surfaces, and block surfaces of the dam is performed using polyurethane, an extruded benzene board, a thermal insulation quilt, and other materials. Fully covered curing is conducted by running a water pipe and operating other curing methods to ensure that the concrete surface is wet. The thermal insulation door is used to close off and insulate the gallery, orifice, and other detailed structures throughout the year. Moreover, an ultrasonic humidifier is used to cure the surface concrete of the gallery, so as to reduce the cracking risk from environmental changes.

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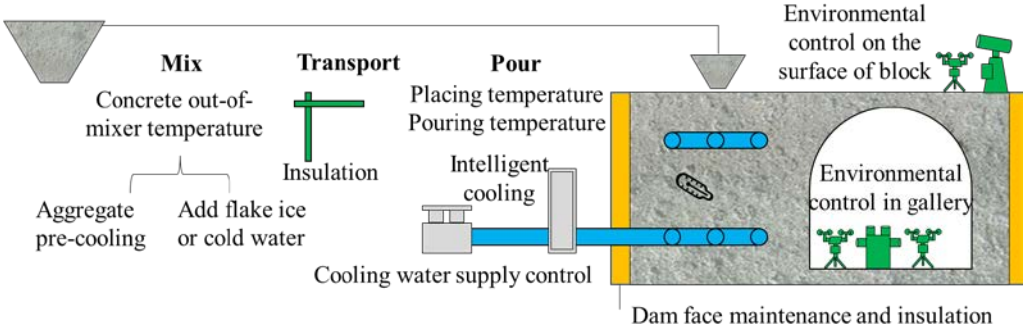

Fig. 4 History of dam thermal anti-cracking safety control

4 Intelligent management for thermal anti-cracking safety during the entire dam lifecycle

The construction of a concrete arch dam is essentially a continuous transformation of a structural system. To dynamically optimize and accurately control the spatiotemporal evolution of long-term anti-cracking safety, in the temporal dimension it is necessary to coordinate the lifecycle work regarding planning, design, construction, and operation, and accordingly tackle four major difficulties. These dif-

ficulties include dam foundation rock quality, concrete thermal anti-cracking, structural safety, and curtain anti-seepage reliability controls. In terms of the spatial dimension, the construction of different parts of the rock foundation, dam body, and detailed special structures must be coordinated. Particular attention should be paid to key parts, such as the foundation concrete, the contact part between the lower part of the steep slope dam section and the bedrock, the gallery in the dam, the diversion orifice, and the flood discharge orifice.

Comprehensive concrete temperature control measures should be formulated for the entire process via material optimization, performance tests, and intelligent control of the construction process and quality. Through coupling analysis and interacting management of the structure and construction progress, the design shape of the dam is optimized, and the image and continuity of pouring are controlled. Specific measures in this construction management approach mainly include the establishment of key management characteristics for full-lifecycle safety control, and the development of a digitally integrated management platform. In this way, the data and information can be interacted with and shared efficiently.

4.1 Co-control of thermal anti-cracking safety characteristics during the entire lifecycle

Based on the construction management practices implemented at the Xiluodu, Wudongde, and Baihetan dams, and considering the multidimensional construction management objectives of progress, quality, and safety, five key safety characteristics are proposed for the full lifecycle of concrete arch dam construction. They include homogeneity, continuity, proportionality, integrity, and durability (HCPID) (Fig. 5). These characteristics reflect the anti-cracking capacity and spatiotemporal working behavior of the dam structure.

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Thermal anti-cracking safety ≈ Strength / Stress

	Homogeneity	Continuity	Proportionality	Integrity	Durability
Interpretation	The shape, quality, strength, stress, and deformation of bedrock and dam are homogenous.	Continuous transformation of the profession and working procedure, timely and smooth transformation of structural system	The construction process is with a proportional dam shape, stable structural system, controlled deformation, and safe stress.	The dam structure and foundation resistance body are complete, and the concrete is without cracks.	Sustainability of dam performance
Requirements	Ensure that the strength of the bedrock is uniform, the foundation surface is smooth, the pouring concrete is homogenous and dense, the heat exchange is uniform, and the geological defects of the bedrock are effectively treated.	The orderly and reliable input of construction resources, such as machinery and equipment, ensures the smooth transition of foundation excavation, foundation treatment, and concrete pouring.	Ensure the orderly implementation of block pouring and joint grouting, realize the stress conversion from cantilever to arch ring of single dam section, and make the structural deformation and stress controlled.	Ensure that the major defects of the foundation resistance body are properly controlled and reinforced, and ensure that the concrete is without cracks, the detailed structure is rigorous, and the joint grouting is dense.	Ensure that the concrete is fully insulated and cured, the defects are properly treated, the concrete strength development meets the design requirements, the seepage is controlled, and the structure is safe and stable.
Control indicators	Stiffness, stress, the heat of hydration, flatness, strength, and temperature of replacement concrete	Pouring interval, pouring block preparation, thermal insulation, and serviceability rate of construction equipment.	Cantilever height, maximum height difference, and adjacent height difference	Concrete anti-cracking safety and rock mass quality	Temperature, admixture, autogenous volume deformation, and strength development
Control methods	1. Foundation treatment methods such as excavation backfilling and consolidation grouting; 2. The stability and accuracy of the concrete construction process, including material mix ,vibrating, and pipe cooling, etc.	1. Strictly control the duration of foundation excavation and other stages; 2. Control the pouring interval to reduce the cracking risk caused by the delay of subsequent processes such as temperature control and grouting caused by a long interval.	1. The whole process control of pouring; 2. Pipe cooling control; 3. Joint grouting process control; 4. Interlayer interval control.	1. Foundation treatment methods such as concrete replacement and consolidation grouting; 2. Materials, body shape design, temperature control, and other comprehensive crack prevention measures; 3. Design of auxiliary structures such as cushions, expanded foundation, and fillet.	1. Add superplasticizer and active mineral admixture; 2. Eliminate the structural damage factors of concrete; 3. Ensure the strength of the concrete.

H C P I D

Fig. 5 Co-control of five key characteristics of concrete dam thermal anti-cracking safety

Taking the construction of a 300-m-level super-high arch dam as an example, the arch dam is a statically indeterminate structural system, in which horizontal arches and vertical beams jointly bear the reservoir water pressure. The huge reservoir water pressure is transmitted to the resistance bodies on both banks through the cooperative work of horizontal arches and vertical cantilever beams. Dam foundation treatment, concrete pouring, temperature control, and joint grouting affect the stress and deformation of the dam foundation structure, thereby affecting the anti-cracking safety of the concrete dam. Owing to the limited construction capacity and temperature control technology of the construction process, the arch dam needs to be poured in sequence according to the blocks cut by joints. The dam is divided into several dam sections 15–20 m wide in the cross-river direction. For each dam section, the dam needs to be poured in 1.5–4.5 m high layers (or lifts) from the foundation surface. The concrete is poured in lifts to form a cantilever beam structure. After the internal temperature of the concrete dam becomes stable through pipe cooling and other measures, the transverse joints between the dam sections are grouted to form the integrity of the dam. Because of the continuous transformation of the stress of the dam foundation, the anti-cracking capacity changes with time. The coordinated control of structural HCPID serves to regulate the concrete temperature gradient in time and space, so as to ensure the anti-cracking safety of the structure during construction (please refer to Section S1 for an application discussion on the Xiluodu dam). In general regarding the arch dam anti-cracking system, integrity and durability are its goals, homogeneity is its basis, and continuity and proportionality are its means of control.

4.2 Intelligent management platform for dam thermal anti-cracking safety control

Actual control of spatiotemporal temperature evolution and the HCPID rely on the development of construction technology and management methods. Through comprehensive perception, real analysis, real-time control, and continuous optimization for anti-cracking safety across lifecycles, the construction of dams without significant thermal cracking has become more feasible. With real dynamic evaluation and real-time closed-loop control of anti-cracking safety in the entire process of concrete dam construction, the knowability, analyzability, predictability, and controllability of anti-cracking safety in project construction can be realized, thereby improving construction capacity and performance. After recognizing that pipe cooling is the core measure for controlling the evolution of the spatiotemporal temperature gradient in concrete dams, an intelligent cooling control system was developed and applied in Xiluodu based on a digital dam project (Lin et al., 2013), with satisfactory thermal anti-cracking control results. Furthermore, a series of applications of intelligent construction technology has been comprehensively conducted in Wudongde and Baihetan to solve key challenges, such as full process intelligent temperature control, intelligent progress management, and coupled simulations of actual working behavior (Fan et al., 2021).

To ensure dynamic perception, analysis, and control of HCPID, based on the construction of the Xiluodu, Baihetan, and Wudongde projects, an intelligent construction management platform (iDam) was developed through integration of technologies such as the Dam Panorama Information Model, Geographic Information Systems, Management Information Systems, Location-Based Services, and Dam Construction Simulations; these provide basic data support for all parties involved in the construction efforts, helping them tackle important problems in an integrated manner, identify key characteristics, and achieve coupled and intelligent closed-loop control of vital processes (Fig. 6). Overall, digital design, intelligent construction, and smart operation based on building information modeling have become popular development directions in the field of hydropower engineering (Zhang et al., 2023).

Using the iDam platform, intelligent management for dam thermal anti-cracking safety control can apply temperature control strategies based on closed-loop control theory. Specifically, this is accomplished by investigating the concrete cracking mechanism in the construction process and optimally controlling the spatiotemporal temperature evolution through the intelligent cooling control system. The basic functions of this platform include temperature control, standard management, equipment diagnosis, exception handling, warnings, predictions, data analysis, quality evaluation, and other processes

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(Ning et al., 2022b). Based on the multidimensional data of thermal anti-cracking control, correlation and goal-oriented control rule analyses (Li et al., 2022) can be performed to optimize the structure, progress, and temperature control strategies. In this manner, practitioners can harness the effectiveness of various intelligent systems for thermal anti-cracking safety control.

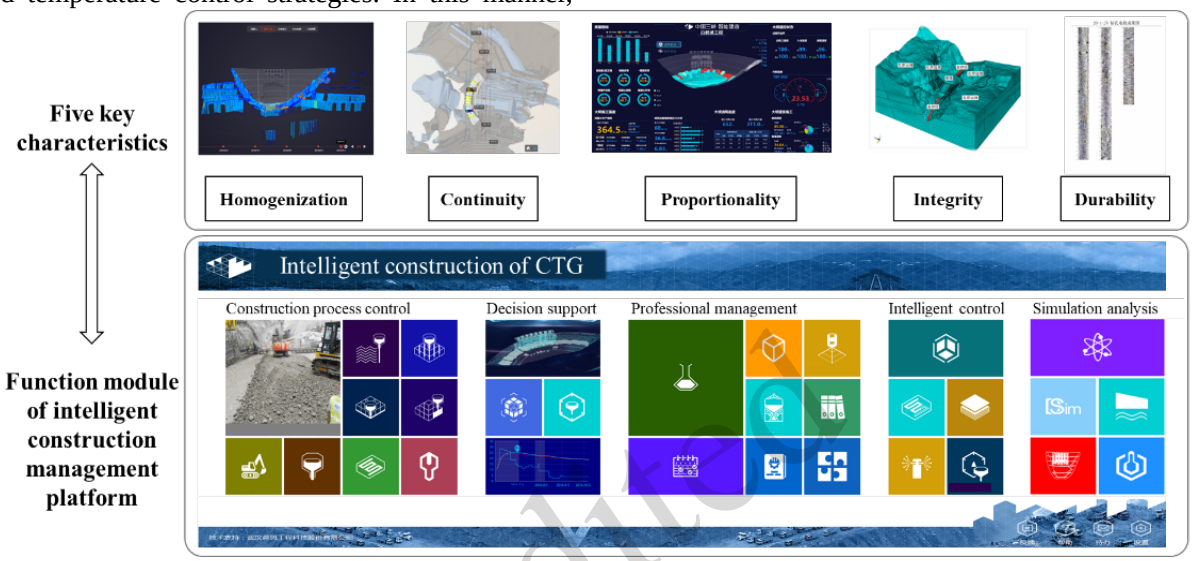

Fig. 6 Intelligent construction management platform based on HCPID

4.3 Discussion on safety management of dams throughout their lifecycles

In addition to the management of dam structural safety during construction, the management of safety during hydropower station operation is also particularly important. The main approach currently adopted for this goal is to establish corresponding warning rules and indicators based on monitoring data; some high dams and large reservoirs will also adopt regular numerical simulations for structural safety analysis and review. Long term monitoring and analysis of structural cracks, seepage channels, geological defects, etc. are particularly important for dam safety management during the operational phase (Hu and Wu, 2018). Compared with the construction period, changes during the operation period are mainly reflected in: (1) load changes caused by the upstream water level shifts; (2) dynamic loads caused by sudden geological disasters such as earthquakes and landslides; (3) durability of materials (Wu et al., 2025); and (4) the evolution of concrete cracks during construction and operation (Zheng et al., 2015).

Looking at the entire lifecycle, dams serve as key elements supporting flood control, power generation, navigation, and other important functions. Their lifespan directly determines the service life of their associated hydropower stations. Based on analysis of the construction period characteristics and changes in the operating conditions of dams, scientific evaluation and prediction of the safety status and ultimate lifespan of dams is a current research hotspot. It is vital for dam managers to establish a corresponding structural operation performance prediction model by analyzing temporal changes in dam deformation, stress, strength, seepage pressure, and other parameters, as well as their respective relationships with structural safety. In recent years, with the development of information technologies such as the Internet of Things, artificial intelligence, and big data, real-time analysis and prediction of dam status have become feasible. The concept of dam safety management which is real-time, online, and intelligent across full lifecycles has gradually become a consensus in the industry.

5 Case study

The Baihetan Hydropower Station is the second cascade in the lower reaches of the Jinsha River, with a total installed capacity of 16,000 MW, making it the world's second-largest hydropower station behind the Three Gorges Hydropower Station. The dam is a concrete hyperbolic arch dam with a maximum height of 289 m and a total pouring volume of over 8 million

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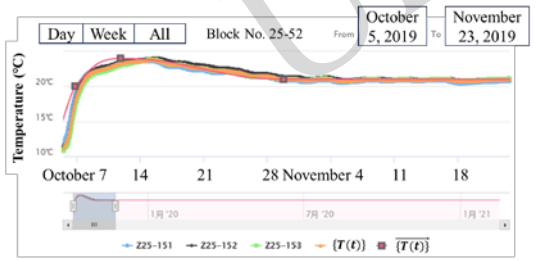
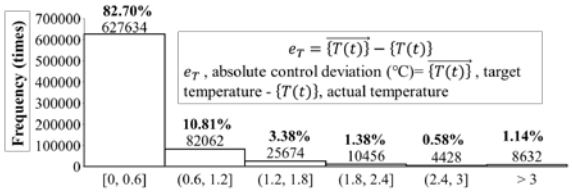
m3. It started pouring in April 2017 and was poured to its top by the end of May 2021. The dam faces several challenges in terms of thermal anti-cracking control, such as structural asymmetry, the first comprehensive application of low-heat cement concrete, high pouring strength, frequent strong winds, and dry hot valleys.

Through the comprehensive application of multiple thermal anti-cracking technologies (such as intelligent cooling control), the spatiotemporal evolution of the concrete temperature can gradually proceed according to the ideal process preset in the design (Fig. 7a). This significantly reduces the risk of dam cracking and ensures the construction of dams without significant cracks. Fig. 7b shows the distribution histograms of the absolute and relative control deviations of the 2,194 blocks of the Baihetan Dam, throughout its entire age. The data shows that the average absolute control deviation is 0.40°C, and the main body is distributed within 3°C, accounting for 98.86%. The compliance rate of the highest temperature of the concrete exceeds 97%, and the compliance rate of the cooling rate is over 98%. Thus, the thermal cracking of the dam concrete has been effectively controlled.



(a) Temperature control curve of the concrete block



(b) Distribution of absolute control deviation (℃)

Fig. 7 Actual temperature control effect of Baihetan

Owing to variations in dam structures, geological conditions, and construction environments across different projects, comprehensive control schemes for anti-cracking safety will differ. Technologies such as material mix optimization, interval period control, full process temperature control, and digital management are effective approaches for improving structural anti-cracking safety. The key to constructing a crack-free dam is to ensure that the tensile strength or allowable tensile stress of the structure in time and space exceeds the actual tensile stress of the structure through the combined application of control measures; in this manner, the structure can possess a sufficient safety margin against cracking. Our proposed anti-crack safety control method for concrete dam construction has been successfully applied in Xiluodu, Wudongde, Baihetan, and other projects, and achieved satisfactory results. Various anti-cracking control schemes have been formed (Table S2) and can be used as a reference for anti-cracking design and construction in similar projects.

6 Conclusions

Based on thermal anti-cracking control of 300-m-level superhigh arch dams, such as the Xiluodu, Wudongde, and Baihetan projects in China, we investigated anti-cracking safety control in concrete dams. To construct dams without significant thermal cracks, a comprehensive technology system for anti-cracking safety control was established, with concrete quality serving as the basis, progress as the thread, full process temperature control technologies (including precooling concrete, intelligent cooling control, fully covered curing, and insulation) serving as the core drivers, and the intelligent construction management platform acting as a practical interface.

The specific anti-cracking safety control technologies include (i) the production of hydraulic concrete materials with better anti-cracking capacity; (ii) a continuous transition from foundation treatment to concrete pouring, employing consolidation grouting technology without covering weight; (iii) leveraging progress-temperature-behavior coupling simulations to reduce the heterogeneous cracking risk caused by long intervals; and (iv) accurate space–time temperature evolution control through closed-loop intelligent technology based on the understanding that the thermal stress is mainly influenced by the temperature gradient, which can be controlled via pipe cooling.

The HCPID are core management factors for achieving objectives of project progress, quality, and safety in dam construction. Knowledge and handling of the HCPID factors can be realized through intelligent management and control technologies. Our novel methodology has been successfully applied in Xiluodu, Wudongde, Baihetan, and was extended to

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TB, NY (abbreviation of hydropower station name), and other dams. Compared with the traditional single temperature control method, the flexible application of the proposed technical system achieves a compliance rate of over 96% for key indicators such as temperature variation, which can significantly reduce cracking risk in hydraulic concrete structures. The positive results regarding construction practice with multiple high arch dams in the lower reaches of the Jinsha River in China can provide a reference for thermal anti-cracking safety design and construction management in other projects.

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Author contributions

Qixiang FAN designed the research. Zeyu NING and Peng LIN processed the corresponding data. Zeyu NING wrote the first draft of the manuscript. Qixiang FAN, Wenfu CHEN, and Guo LI helped to organize the manuscript. Qixiang FAN revised and edited the final version.

Conflict of interest

Qixiang FAN, Zeyu NING, Peng LIN, Wenfu CHEN, and Guo LI declare that they have no conflict of interest.

References

Adek T, Anita S, 2019. Effect of Cooling Water Temperature and Space between Cooling Pipes of Post-cooling System on Temperature and Thermal Stress in Mass Concrete. Journal of Building Engineering, 24:100731.

An RN, Lin P, Chen DX, et al., 2024. An intelligent cooling control system for mitigating the cracking risks of mass concretes. Advances in Concrete Construction, 17 (5): 257-271.

Chen GX, Liu YX, Ji GJ, et al., 2021. Research on the Application of Low-heat Portland Cement in Hydraulic Concretes. Water Resources and Hydropower Engineering, 52(12):191-200 (in Chinese).

Chen WF, Li QB, Yang J, et al., 2021. A Treatment Method for V-shaped Valley Dam Foundation. Chinese Patent 202110824841.4.

Fan QX, Deng ZY, Lin P. et al., 2022. Coordinated deformation control technologies for the high sidewall—bottom transfixion zone of large underground hydro-powerhouses. Journal Of Zhejiang University-science A, 23, 543–563.

Fan QX, Lu YM, Li G, et al., 2021. Innovation and Practice of Intelligent Construction Management of Largescale Hydropower Projects on the Lower Jinsha River. Journal of management world, 37(11): 206~226 (in Chinese).

Fan QX, Yang HQ, Li WW, et al., 2018. Comparison of Thermal and Mechanical Properties Between Low-heat and Medium-heat Portland Cement Concrete. Journal of Yangtze River Scientific Research Institute, 35(12):133-137 (in Chinese).

Fan QX, 2017. Technology improvements and management innovations in construction of Xiluodu hydropower station on Jinsha River. Frontiers of Engineering Management, 4(2): 231.

Fan QX, Li YQ, Zhang SB, et al., 2016a. Preparation Method of Medium Heat Cement for High Arch Dam. Chinese Patent 201610113540. X.

Fan QX, Hong WH, Zhou SW, et al., 2016b. Temperature Control and Crack Prevention Method of Mass Hydraulic Concrete for Super-high Arch Dam. Chinese Patent ZL201610035270.5.

Fu S, He T, Wang GL. et al., 2011. Evaluation of cracking potential for concrete arch dam based on simulation feedback analysis. Science China Technological Sciences, 54(3): 565-572.

Guan T, Zhong DH, Ren BY, et al., 2018. Construction simulation of high arch dams based on fuzzy Bayesian updating algorithm. Journal Of Zhejiang University-science A, 19, 505–520.

GAQSIQ (General Administration of Quality Supervision, Inspection and Quarantine), 2017. Moderate-heat portland cement, low-heat portland cement. GB/T200. National Standards of the People's Republic of China.

Gong FY, Sun XJ, Takahashi Y, et al., 2023. Computational modeling of combined frost damage and alkali–silica reaction on the durability and fatigue life of RC bridge decks. Journal of Intelligent Construction, 1, 9180001.

Hu J, Wu SH, 2018. Statistical modeling for deformation analysis of concrete arch dams with influential horizontal cracks. Structural Health Monitoring, 18(2):546-562.

Jia JS, 2016. A Technical Review of Hydro-Project Development in China. Engineering, 2 (3): 302-312.

Ji T, 2010. Application of Low-heat Portland Cement in Hydraulic Concrete. The 10th Youth Academic Exchange Conference of China Academy of Water Resources and Hydropower Sciences.

Li M, Lin P, Chen DX, et al., 2022. An ANN based short-term temperature forecast model for mass concrete cooling control. Tsinghua Science and Technology,28(3): 511–524

Lin P, Peng HY, Fan QX, et al., 2021. A 3D Thermal Field Restructuring Method for Concrete Dams Based on Re-

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al-Time Temperature Monitoring. KSCE Journal of Civil Engineering, 25 (4): 1326-1340.

Li WW, Fan QX, Li XY, et al., 2017. Development and Application of Specific Low Heat Portland Cement for Building ultra-high Arch Dams. Journal of Hydroelectric Engineering, 36(03):113-120 (in Chinese).

Lin P, Li QB, Zhou SW, et al., 2013. Intelligent Cooling Control Method and System for Mass Concrete. Journal of Hydraulic Engineering, 44(08):950-957 (in Chinese).

Niu XQ, 2022. The Three Gorges Project. Engineering,15: 17-23.

Ning ZY, Lin P, Ouyang JS, et al., 2022. Intelligent cooling control for mass concrete relating to spiral case structure. Advances in Concrete Construction, 1 (14): 57-70.

Ning ZY, 2022. Theory and Application of Intelligent Cooling Control for Super-high Arch Dam. PhD Thesis, Tsinghua University. Beijing, China.

Peng HY, Lin P, Xiang YF, et al., 2020. A Positioning Method of Temperature Sensors for Monitoring Dam Global Thermal Field. Frontiers in Materials, 7: 587738.

Peng HP, Lin HM, 1987. Concrete Temperature Control of Dongjiang Double Curvature Arch Dam. Water Power, 11:44-48 (in Chinese).

Shi YL, Wu K, Hu Y, et al., 2015. Testing Study on Early Cracking Resistance of Low Heat Concrete. Concrete, 04:29-31 (in Chinese).

Sun XJ, Wang SQ, Jin JP et al., 2023. Computational methods of mass transport in concrete under stress and crack conditions: A review. Journal of Intelligent Construction, 1, 9180015.

Tang ZM, Zhang J, 2011. Design of Treatment for Cracks in Jinping-I Arch Dam. Proceedings of the 11th National Hydraulic Concrete Building Repair and Reinforcement Technology Exchange Conference.

Wang L, Yang HQ, Zhou SH, et al., 2018a. Mechanical properties, long-term hydration heat, shrinkage behavior and crack resistance of dam concrete designed with low heat Portland (LHP) cement and fly ash. Construction and Building Materials, 187: 1073-1091.

Wang QW., Zhong DH., Wu BP. et al., 2018b. Construction simulation approach of roller-compacted concrete dam based on real-time monitoring. Journal Of Zhejiang University-science A, 19, 367–383.

Wang JM, Duan SH, Zheng J, et al., 2015. Key Construction Techniques of 4.5m Thick Warehouse Layer Level I Super High Concrete Arch Dam. South-to-North Water Transfers and Water Science & Technology, 13(3):580-584 (in Chinese).

Wang WM, Ding JX, Wang GL, et al., 2011. Stability analysis of the temperature cracks in Xiaowan arch dam. Science China Technological Sciences, 54 (3): 547-555.

Wang RK, 2009. Research and Development of Concrete Materials and Temperature Control for Hydraulic Dams. China Water & Power Press. Beijing, China (in Chinese).

Wang Z, Maekawa K, 2022. Lifetime assessment of structural concrete – multi-scale integrated hygrothermal-chemo-electrical-mechanistic approach and statistical evaluation. Structure and Infrastructure Engineering, 18:7, 933-949.

Wang Z, Gong FY, Maekawa, 2023. Multi-scale and multi-chemo–physics lifecycle evaluation of structural concrete under environmental and mechanical impacts. Journal of Intelligent Construction, 1, 9180003.

Wu RJ, Wang YZ, Khant SH, et al., 2025. An enhancement method for chloride diffusion coefficient long-term prediction based on Hilbert dynamic probabilistic interpolation and BO-LSTM. Measurement, 247, 116820.

Xie XF, 1983. Practical Analysis of the First Application of Air-cooled Aggregate in Gezhouba Project. Yangtze River, 6:1-7 (in Chinese).

Yang H, Tu XY, Xi ZY, 2010. Monitoring of Cracks in Arch Dam in Ertan Project and Analysis of Control Measures. Pearl River, 31(06):66-69 (in Chinese).

Yang N, Liu Y, Qiao Y, et al., 2021. Intelligent Spray Control for the Concrete Curing of Mass Concrete Bins. Journal of Tsinghua University (Science and Technology), 61(07):724-729 (in Chinese).

Yang WM, Song HX, 2021. The World's Largest Hydropower Station Un-der Construction - the Pour of Baihetan Hydropower Station Dam is Completed. People's Daily.

Zhang ZL, Zhang SR, Zhao ZY, et al, 2023. HydroBIM—Digital design, intelligent construction, and smart operation. Journal of Intelligent Construction, 1, 9180014.

Zhang GX, Liu Y, Liu YZ, et al., 2018. Reviews on Temperature Control and Crack Prevention of High Concrete Dam. Journal of Hydraulic Engineering, 49(09):1068-1078 (in Chinese).

Zhong DH, Zhao CS, Ren BY, 2011. Research on analysis method for temperature control information of high arch dam construction. Science China Technological Sciences, 54 (S1): 40-46.

Zhang CR, Fan QX, Pan JZ, et al., 2010. All Cracks Shall Be Prevented During Concrete Pouring of Xiluodu Dam. China Three Gorges Project News, 2010-7-5. (in Chinese).

Zheng SR, 2009. Innovations in Concrete Design, Temperature Control and Anti-cracking Techniques for Concrete Construction of Three Gorges Dam. Advances in Science and Technology of Water Resources, 29(05):46-53. (in Chinese).

Zheng XQ, Gu CS, Qin D, 2015. Bootstrap-typed criterion studies of online diagnostic to cracks abnormality of concrete dam. European Journal of Environmental and Civil Engineering, 20(07): 737-747.

Zhu BF, 2012. Thermal Stresses and Temperature Control of Mass Concrete (2nd Edition). China Water&Power Press, Beijing, China.

Zhu BF, 2006. On the Feasibility of Building High-Quality Arch Dams without Cracking and the Relevant Techniques. Journal of Hydraulic Engineering, 10:1155-1162 (in Chinese).

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Electronic supplementary materials
Table S1, Table S2, Section S1

中文概要

题　目：混凝土坝抗裂安全控制方法研究

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目　的：“无坝不裂”难题一直困扰着水工结构的设计、施工与运行。本文旨在探讨混凝土坝抗裂安全控制过程中需要采用的关键技术及管理方法，形成混凝土坝抗裂安全控制成套方法与技术体系，以提高混凝土坝的施工质量。

创新点：1. 建立了以建设无温度裂缝大坝为目标，以混凝土品质为基础、进度为主线、制冷混凝土+智能通水+全面养护保温等全方位温控技术为核心的混凝土抗裂安全综合控制措施；2. 形成了中低热水泥混凝土制备、以间歇期为控制要素的进度-性态-温度耦合仿真分析、以通水冷却为核心的智能温控、全坝全过程数字化管控等成套关键技术体系；3. 提出了以均匀性、连续性、均衡性、完整性和耐久性为核心的混凝土筑坝管理要素。

方　法：1. 基于“感知、分析、控制”闭环理论研发了以智能通水为代表的成套温控防裂系统；2. 通过材料试验，确定了中低热水工混凝土制备方法；3. 通过理论推导，揭示了抗裂安全控制的核心是要控制大坝的时空温度演化过程。

结　论：1. 提高混凝土抗裂性能、合理规划施工进度、开展全过程精细化智能温控是解决无坝不裂难题的重要技术手段。2.关键技术包括中低热水工混凝土制备、无盖重固结灌浆、进度-温度-性态耦合仿真、全过程全面智能温控等。3. 均匀性、连续性、均衡性、完整性和耐久性是实现工程进度、质量、安全等目标的核心管理因素。研究成果已在溪洛渡、乌东德、白鹤滩等地成功应用，并推广到 TB、NY 等大坝，为类似工程的抗裂安全设计和施工管理提供了参考。

关键词：混凝土坝；温控防裂；智能通水；水工混凝土

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