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**Research paper**

# Application of pre-embedded cold water pipe technology in large volume concrete dams

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**Abstract:** To address the issue of heat release during the construction of concrete dams, this study employs the approach of embedding water pipes for temperature control. Taking a large-volume concrete gravity dam in China as an example, considering environmental and river water temperatures, inputting concrete thermodynamic parameters, and taking various factors such as pipe layout, calculation parameters, pipe radius, material, spacing, and water temperature into account, the study utilizes finite element software for simulation modeling. It systematically discusses the relationship between cooling effects, costs, and engineering safety. The research results indicate that, under the condition of a rectangular section layout, with a pipe radius of 0.01 m and a spacing of 1.5 × 1.5 m, the comprehensive effect is optimal. The influence of different pipe materials on temperature reduction is minimal. When changing pipe materials, only material costs and their impact on structural safety and durability need consideration. Additionally, excessively low water temperatures during water passage can lead to internal concrete cracking, requiring attention during construction.

**Keywords:** cold water pipeline, concrete dam, construction technology, finite element, safety economy

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# 1. Introduction

The heat release problem in the construction of mass concrete has been the key and difficult point to be overcome in the project for a long time [1–3]. For example, in construction engineering, especially in water conservancy engineering, there are a lot of different types of large volume concrete structures, taking the common concrete arch dam as an example. As shown in the Fig. 1, in the main construction area of the dam section, the heat released when the condensation and hardening will seriously affect the progress of the project and endanger the safety of the personnel.

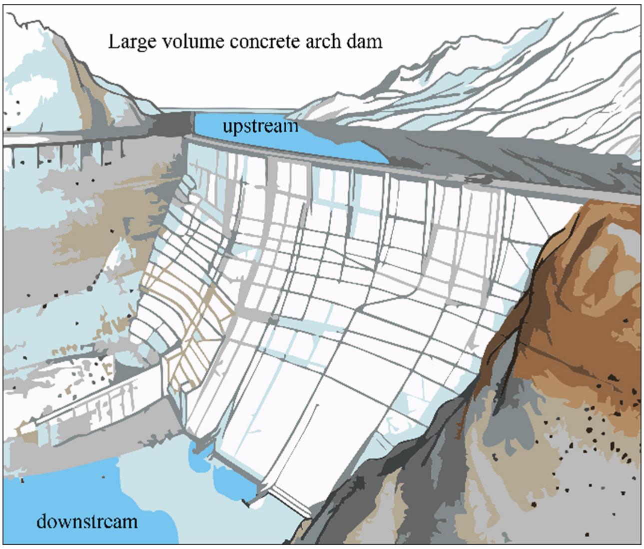


Fig. 1. Schematic diagram of a common concrete arch dam

In the traditional temperature control solutions, engineering technicians control the heat release of the mass concrete structure by designing raw materials and mixing ratio of the concrete [4, 5], developing cement with low hydration heat [6], reducing the environmental temperature and other measures [7]. Looking back at the literature, it can be seen that the essence of these schemes is based on the internal factors of the formation of hydration heat as the starting point, using methods of controlling raw materials and chemical processes for cooling. The commonality is the lack of consideration for external factors in reducing hydration heat. A large amount of engineering experience has shown that simple internal factor control is effective to a certain extent, but there are problems such as high cost, uneven temperature control effect, later cracking [8], and environmental pollution [9–11].

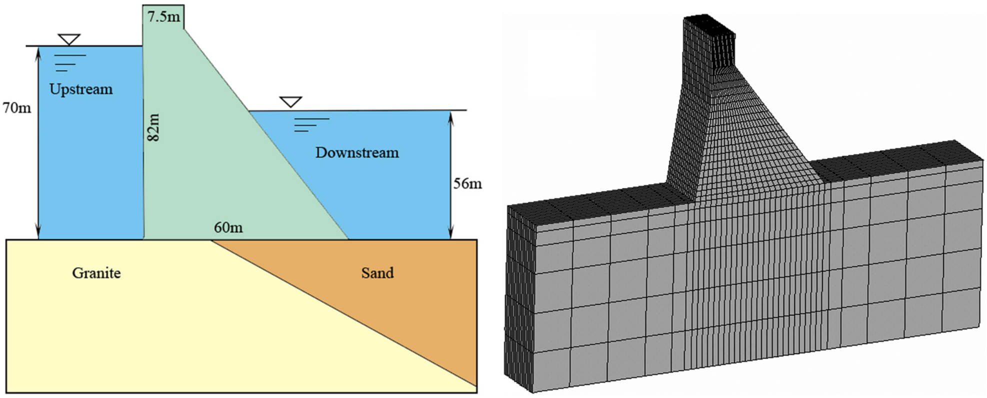
Among temperature control schemes based on external influencing factors, the most widely used technical means is water cooling [12–14], which has the advantages of good effect, low cost, and controllable temperature. In the past 20 years, a relatively complete theoretical system has been formed [15–17]. Piyius et al. [18] discussed the effect of cold water pipes on the early temperature stress of large volume concrete; Myers et al. [19] established a mathematical model for reducing hydration heat in concrete during construction by cooling water pipes. They simplified the cooling process to solving a one-dimensional heat equation, providing guidance for the design of cooling systems; Xu et al. [20] based on the formula of mixture temperature, the cooling effect of various raw materials on concrete was calculated, and the cooling scheme of raw materials meeting the requirements of target inlet temperature was determined; Lin et al. [21] adopted closed-loop control in the principle of automatic control, which can quickly reduce the temperature of the structure; The Liu et al. [22] research group of China Research Institute of Water Resources and Hydropower independently developed a simulation testing machine for the entire process of water cooling, which couples temperature and related thermodynamic parameters that can conveniently adjust the temperature. In fact, as of December 2023, there were over 2500 Chinese academic papers related to "large volume concrete, temperature control" as the keyword search. Although these achievements can theoretically control temperature well, considering the knowledge background of on-site construction personnel, using overly complex calculations and expensive equipment is not practical in the vast majority of construction sites in China, and these schemes are not universal in actual construction. How to find a universal and concise solution to control temperature from the perspective of construction technology is an urgent problem that on-site technicians in China and many developing countries need to solve.

Based on it, the study takes water cooling as the background and starts from the perspective of construction technology, through the scheme of pre-embedded cold water pipes, considering different cold water pipe materials, layout, radius, water flow and other simple factors, combined with finite element software to simulate the temperature field of mass concrete during construction, the most reasonable reducing temperature scheme of embedded cold water pipes is finally selected. The proposed approach about the cold water pipe layout scheme in this article, which has advantages such as concise theory, simple operation, and easy access to materials. It has considerable engineering practical value in developing countries and is repeatable, which can be used as a reference for similar problems in engineering.

## 2. Model and parameters

### 2.1. Finite element calculation model and border conditions

The concrete dam is built on a mixed foundation of granite and sand, with a top width of 7.5 meters, a bottom width of 60 meters, and a height of 82 meters. It belongs to a typical large-volume concrete project. The expected water levels upstream and downstream after completion are 70 meters and 56 meters respectively. The dimensions are calculated as shown in Fig. 2(a). According to the insulation boundary at the bottom-side interface of the dam, the water-air interface at the water surface, and the water-solid boundary at the water-bottom interface of the dam, as well as the free side and fixed foundation boundary conditions, a finite element model is established as shown in Fig. 2(b).




(a) (b)

Fig. 2. Concrete dam and model: (a) The profile map of the dam body in this study, (b) Finite element calculation model of this study

## 2.2. Calculating parameters

**Temperature parameters**

Studies have shown that environmental temperature has a significant impact on large-volume concrete construction. Therefore, this paper considers local air temperature and river water temperature separately in the calculations. The study selected temperature data from meteorological stations in the area of the dam site from 1956 to 2020, and recorded monthly maximum, minimum, and average temperatures. Using measured data from the nearest hydrological station to the dam site from 1980 to 2020, the multi-year average temperature of the river water is calculated. These four temperatures are considered as construction influencing factors, and their trends are shown in Fig. 3.

According to the statistical results from Fig. 3, the local temperature curve shows a pattern of higher temperatures in the middle of the year and lower temperatures at the beginning and end of the year. The high temperature period occurs in the months of June, July, and August, with an average temperature of 26°C during this period, reaching a maximum of 34°C and a minimum of 24°C. This pattern is typical of a northern hemisphere climate. The water temperature curve follows the same pattern as the temperature curve. The highest water temperature in summer reaches 25°C. Such temperatures cannot be ignored during construction. Excessively high temperatures, combined with the heat released during concrete curing, can easily lead to safety issues. This must be taken seriously in engineering projects.

**Thermal parameters**

During construction, some structures are made of high-strength concrete, while the main body of the dam is made of roller compacted concrete (two graded or three graded). The entire dam is poured onto the bedrock, and the thermodynamic parameters of each material are shown in Table 1.

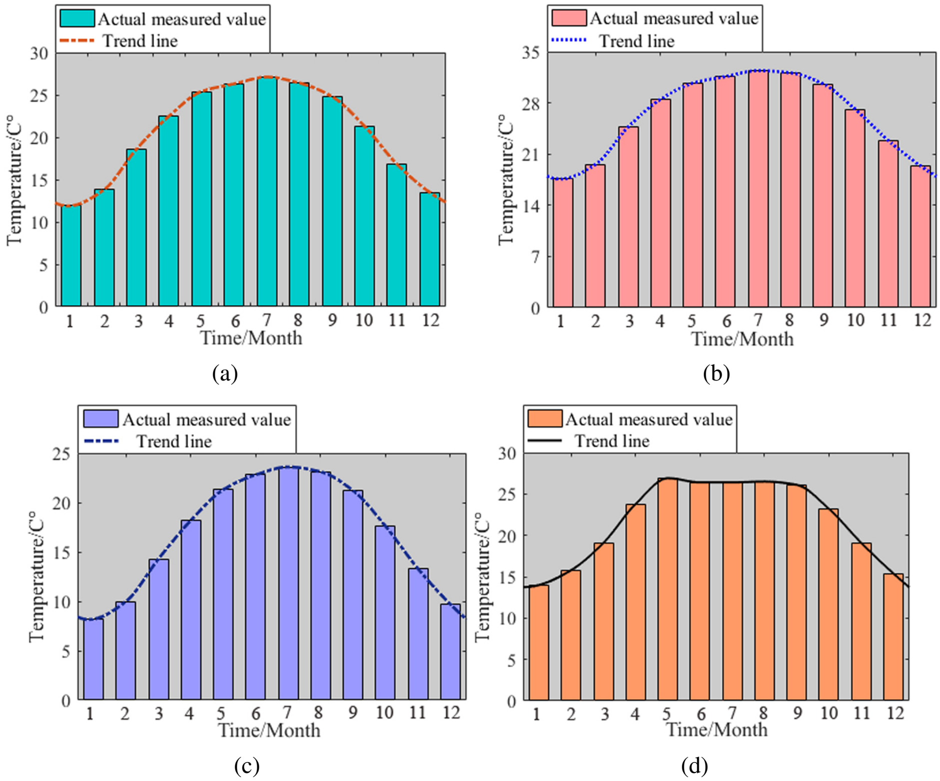



Fig. 3. Temperature parameters: (a) Average temperature, (b) Average maximum temperature, (c) Average minimum temperature, (d) Average river temperature

Table 1. Thermal parameters

| No. | Type of concrete | The normal concrete | RCC | | Bedrock |
|---|---|---|---|---|---|
| | | $C_{15}$ $C_{20}$ | $C_{180}$20 MPa Two graded | $C_{180}$15 MPa Three graded | |
| 1 | Thermal conductivity (kJ/mh°) | 10.6 | 9.4 | 9.4 | 15 |
| 2 | Thermal diffusivity ($m^2$/h) | 0.0045 | 0.0036 | 0.0035 | 0.007 |
| 3 | Specific heat (kJ/kg°) | 0.92 | 0.90 | 0.88 | 0.8 |
| 4 | Linear expansion coefficient ($10^{-6}$/°) | 7.0 | 6.0 | 6.0 | 7.0 |
| 5 | Heat transfer coefficient (kJ/mh°) | 42.0 | 42.0 | 42.0 | 42.0 |
| 6 | Bulk density (kN/$m^3$) | 2400 | 2400 | 2400 | 2700 |

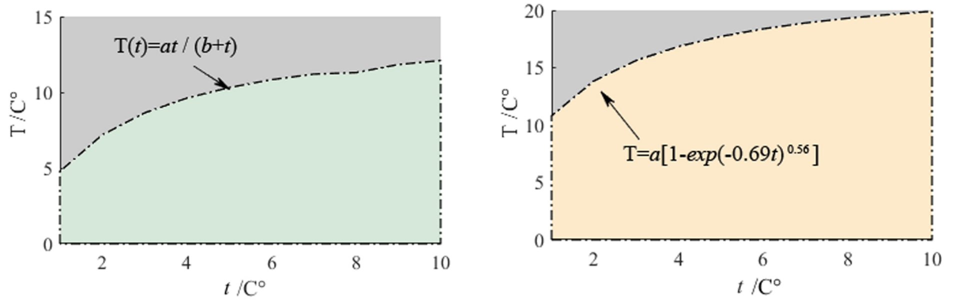
Of the types of concrete shown in Table 1, the adiabatic heating formula of normal $C_{15}$ concrete is:

$$T\,(t) = 21.68 \times [1 - e^{(-0.69t^{0.56})}] \tag{2.1}$$

The adiabatic heating formula of normal $C_{20}$ concrete is

$$T\,(t) = 43.63 \times [1 - e^{(-0.69t^{0.56})}] \tag{2.2}$$

The curve of the adiabatic heating formula of the two types of normal concrete is in the form of $T\,(t) = at/(b + t)$, of which $a$ and $b$ are the constants, as shown in Fig. 4(a).




(a) (b)

Fig. 4. Thermal parameter curve: (a) Adiabatic temperature rise curve of normal concrete, (b) Adiabatic temperature rise curve of RCC

The adiabatic heating formula of the second-graded RCC $C_{180}$ 20 MPa is:

$$T\,(t) = 20.33t/(3.07 + t) \tag{2.3}$$

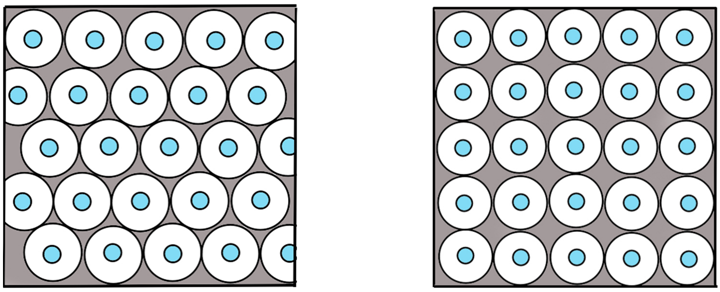
The adiabatic heating formula of the third-graded RCC $C_{180}$ 15 MPa is:

$$T\,(t) = 14.5t/(2.03 + t) \tag{2.4}$$

The curve of the adiabatic heating formula of the two types of RCC is in the form of $T\,(t) = a(1 - e^{-bx^c})$, of which $a$, $b$ and $c$ are the constant, which is shown in Fig. 4(b).

## 2.3. Layout forms of cooling water pipelines

As mentioned earlier, in actual large-volume concrete construction, the technique of embedding cold water pipes for cooling is simple and feasible, and it is very common in many large-scale projects in China. Taking the plum blossom layout and rectangular layout as examples, temperature dead zones will occur in both schemes within a unit section, as shown by the black areas in Fig. 5. Through simple calculations, it can be observed that the black area of the plum blossom layout is smaller, indicating that more cold water pipes can pass through the concrete section, resulting in better cooling effects. However, in reality, this pipe layout scheme requires higher demands on workers. During the concrete pouring process, the formwork is prone to movement, leading to pipe deformation. Therefore, in practical engineering, the rectangular layout scheme as shown in Fig. 5(b) is mostly adopted. The calculations in this paper are based on this scheme.



(a) (b)

Fig. 5. Cold water pipe layout scheme: (a) The plum flower form layout scheme, (b) Rectangle scheme

At this point, the calculation model, parameters, and schemes have all been established. In the following sections, this study conducts single-variable experiments, meaning that while keeping other conditions constant, factors such as pipe radius, pipe material, pipe spacing, and water temperature passing through the pipes are individually adjusted to simulate the heat dissipation temperature of the dam. Ultimately, the heat dissipation effects of each scheme are evaluated.

# 3. Results and discussion

## 3.1. Effect of the radius of cooling water pipelines on the cooling effect

The cooling water pipelines are made of polystyrene plastic pipes with the radius being $r_1 = 0.008$ m, $r_2 = 0.016$ m and $r_3 = 0.032$ m, respectively. The cooling water temperature is 12°C. Water flow starts two days after pouring, the rate of water flow is 24 m$^3$/d and the cooling time is 14d. The temperature duration curve of the center point at 325 m height of the dam is taken, and the calculation results are shown in Fig. 6 in the following.

From Fig. 6, it can be observed that there is a negative correlation between the temperature of the dam and the pipe radius. In other words, as the pipe radius increases, the cooling effect becomes more significant. However, this correlation weakens as the radius increases. When the pipe radius increases from 0.008 m to 0.016 m, the cooling effect is higher than when the radius increases from 0.016 m to 0.032 m (even though the absolute increase in radius is greater in the second scenario). This indicates that solely relying on increasing the pipe radius to improve cooling efficiency is not economical. Moreover, due to technological limitations, the embedded pipes discussed in this study are permanent fixtures. Excessive radius can reduce the overall strength of the dam, leading to structural damage or leakage. This should be considered in practical engineering projects.

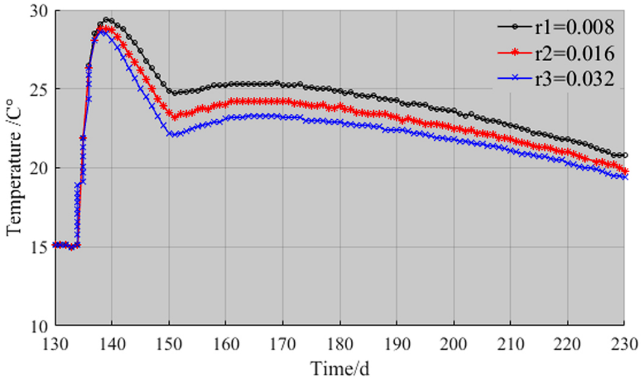



Fig. 6. The influence of cooling pipe radius on the concrete temperature

## 3.2. Effect of the material of cooling water pipelines on the cooling effect

In this study, cast iron pipe and plastic pipe (polystyrene foam tube), which are common in engineering, are selected, and their thermal conductivity coefficient differs greatly, which are 56.88 kJ/mh°C and 2.89 kJ/mh°C respectively and can be effectively used for comparative tests. The water pipes are arranged at equal intervals, the cooling water temperature is 12°C, the rate of water flow is 24 $m^3$/d, and the cooling time is 14 days. The temperature duration curve of the center point at 26 m (absolute height) height of the dam is taken, and the calculation results are shown in Fig. 7.

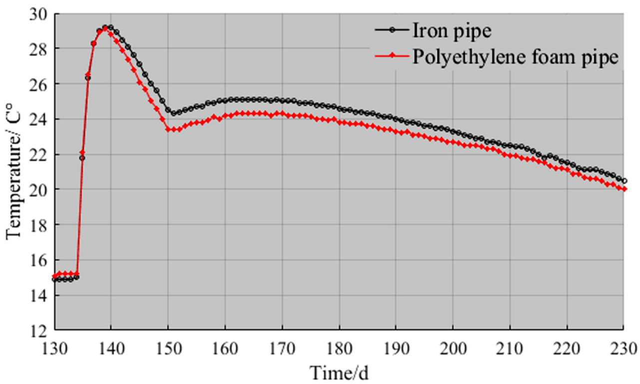



Fig. 7. The influence of the material of cooling pipes on the temperature of concrete

From Fig. 7, it can be observed that there is little difference in the actual cooling effect between cast iron pipe and plastic pipes, with a maximum temperature difference of only 0.44°C. However, considering structural strength, iron pipes are significantly stronger than plastic pipes and are less prone to damage during water flow. Therefore, iron pipes should be preferred in practical engineering projects. This conclusion is consistent with the research findings of Tasri [23].

### 3.3. Effect of the interval of cooling water pipelines on the cooling effect

Four kinds of pipeline layout intervals (respectively $1 \times 1$ m, $1 \times 1.5$ m, $1.5 \times 1.5$ m and $1 \times 3$ m) are selected as the comparative group, and the above intervals are compared with the dam body without any cooling measures. The remaining calculation parameters are the same as stated above, which is shown in Fig. 8.

From Fig. 8, it can be observed that there is a positive correlation between the spacing of pipes and the cooling effect. The smaller the spacing, the better the cooling effect. When the spacing is reduced from 3 m to 1 m, the cooling effect increases by approximately 40%. However, in practical engineering, factors such as material cost and construction technology need to be considered. Too small of a spacing increases material usage on one hand and makes construction inconvenient on the other hand. Therefore, considering the comprehensive factors of cooling effect, material cost, and construction difficulty, this study concludes that a pipe spacing of $1.5 \times 1.5$ m is optimal.

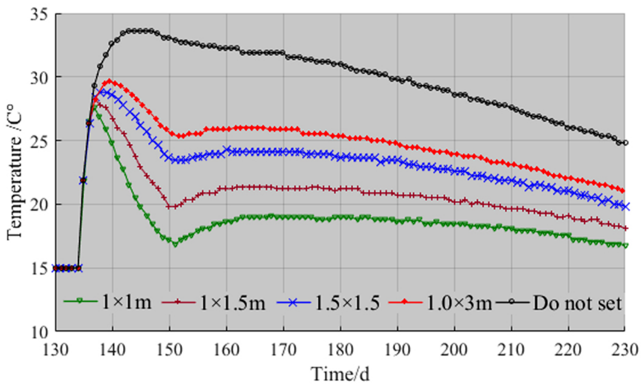



Fig. 8. Change spacing scheme

### 3.4. Influence of the cooling water temperature on the cooling effect

From the previous part, it can be known that when the pipeline interval is $1.5 \times 1.5$ m, the interval scheme is optimal. Based on this scheme, this part chooses four working conditions of water temperature, namely 6°C, 9°C, 12°C and 15°C, for simulation calculation, and the results are shown in Fig. 9.

It can be observed that there is a positive correlation between the water temperature passing through the pipes and the cooling effect. The lower the water temperature inside the pipes, the better the cooling effect on the concrete. This may seem like an obvious conclusion. However, in reality, excessively low water temperatures in practical engineering can lead to temperature differentials between the interior and exterior, resulting in internal temperature stresses and cracking of the concrete. Previous studies have shown that for every 1°C decrease in temperature, the tensile stress within concrete increases by 10 MPa. Additionally, ensuring lower cold water temperatures in the summer requires additional large-scale refrigeration equipment, which adds extra costs. This is not feasible in on-site construction.

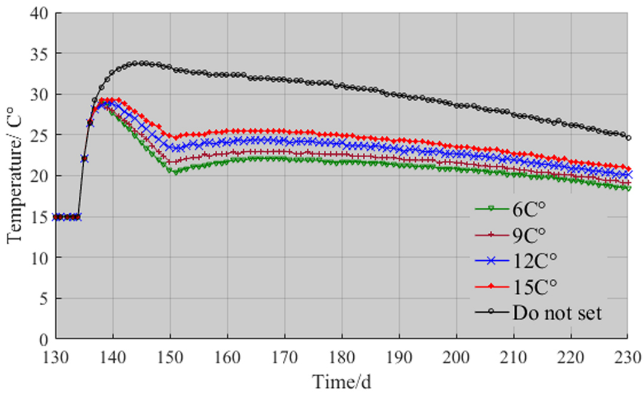



Fig. 9. The influence of the cooling water temperature on the concrete temperature

## 3.5. The final plan of this article

Based on the discussions in the previous sections, the recommended conditions and scheme of this study are as follows: in mid-latitude regions during hot summers, when constructing large-volume concrete structures, the rectangular embedded cold water pipe technique can be employed for cooling. Cast iron pipe with a radius of 0.01 m are preferred (choosing this pipeline size is convenient for production and construction), with a pipe spacing of $1.5 \times 1.5$ m, and the water passing through the pipes should have a temperature of 10°C. This scheme minimizes structural damage from a safety perspective, has lower cost in terms of economics, and is relatively easy in terms of construction difficulty. The layout efficiency and water flow sequence are illustrated in Fig. 10.

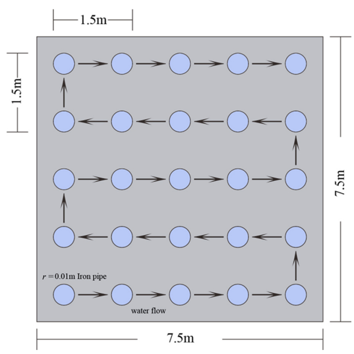
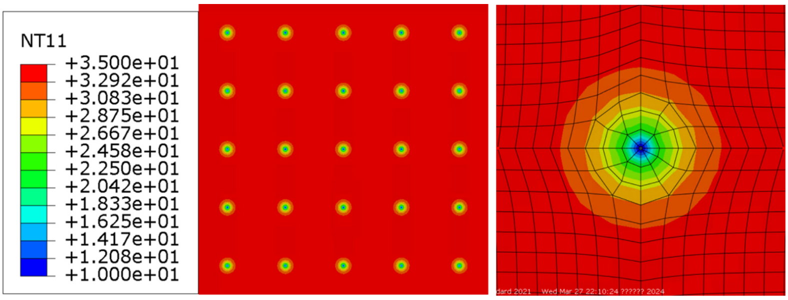
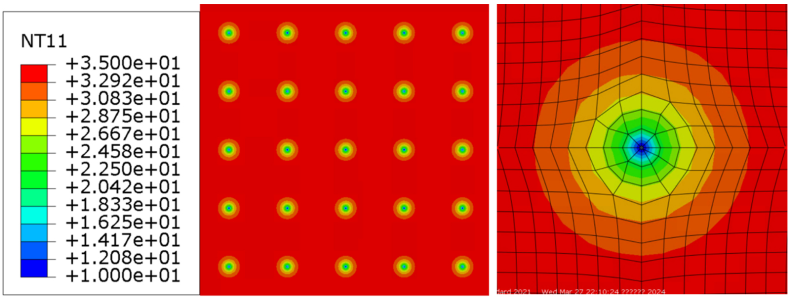



Fig. 10. The recommended pipeline radius, spacing, material, water temperature, and water sequence in this article

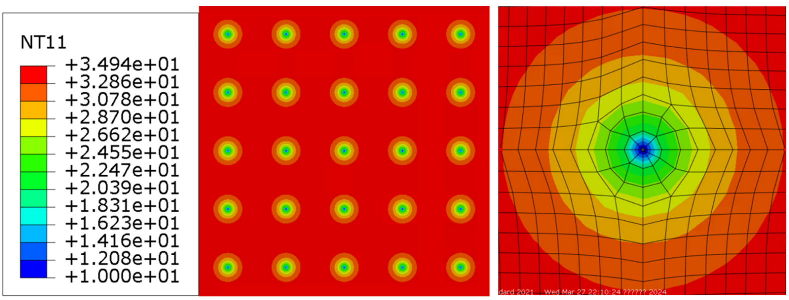
The initial temperature of the concrete is 35°C, and the pipeline is filled with water for 6 hours, 12 hours, 24 hours, the temperature of the concrete changes, as shown in Fig. 11.




(a)




(b)




(c)

Fig. 11. Results of the FEM simulations: (a) Temperature cloud at 6 h – overall cloud 7.5 m (left) local cloud 750 mm (right), (b) Temperature cloud at 12 h – overall cloud 7.5 m (left) local cloud 750 mm (right), (c) Temperature cloud at 24 h – overall cloud 7.5 m (left) local cloud 750 mm (right)

It can be observed that after 24 hours of water circulation cooling, the temperature of concrete at 0.70 m from the center of the pipe has decreased from 35°C to 33°C, indicating a significant cooling effect. Therefore, it is foreseeable that as the water circulation time increases, the cooling range of concrete will further expand. This solution holds practical value in engineering applications.

In the specific control of water circulation cooling, environmental temperature-concrete temperature, and concrete temperature-water temperature are used as comprehensive variables. A two-stage fuzzy algorithm is employed to ensure that the temperature difference between the interior of the concrete and the incoming water is less than 25°C and the daily cooling rate is less than 2°C, in accordance with the national standard of the People's Republic of China (GBT/51028-2015). Since this paper only provides an introduction to construction techniques without delving deeply into mathematical theory, detailed algorithmic principles can be found in reference [24], and the algorithm flowchart is depicted in Fig. 12.

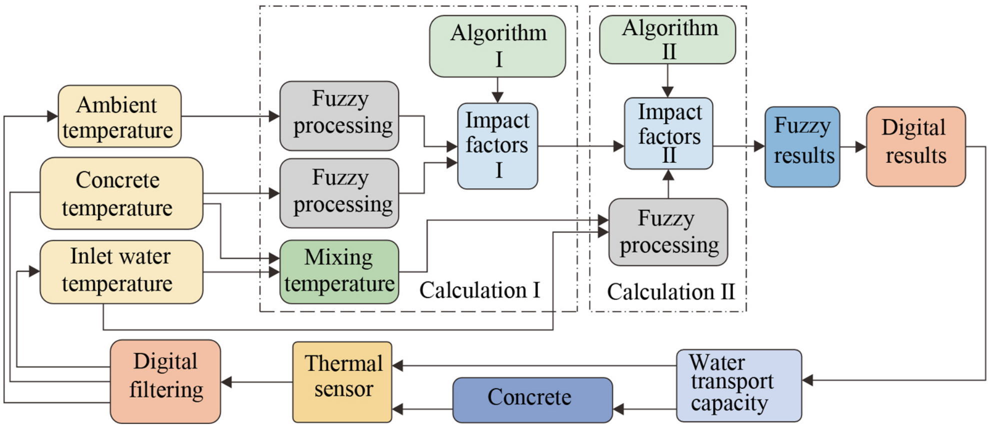



Fig. 12. Temperature control algorithm flowchart

## 4. Conclusions

This paper takes actual concrete dams in China as an example to introduce a commonly used temperature control technique in construction—embedded cold water pipes. Considering environmental factors and economic costs, while basically not reducing the main structural strength, and achieving good cooling effects with the simplest construction scheme, the main conclusions of this paper are as follows:

1. It is recommended to use pipes with a radius of around 0.01 m. When the pipe radius exceeds 0.016 m, the cooling effect increases slowly, and there is a risk of reducing the overall structural strength with the increase in pipe radius.
2. Cast iron pipes are recommended as the main material due to their high strength, fast heat dissipation, low cost, and ease of processing and shaping, making them easily accessible in engineering projects.
3. The spacing between water pipes plays a major role in cooling, but in actual construction, the spacing cannot be too small, as it would increase construction costs and difficulty. Considering concrete formwork, a recommended spacing of $1.5 \times 1.5$ m is suggested.
4. In hot regions, a water temperature of around 10°C is recommended. This prevents excessive temperature differentials that can cause concrete cracking and does not require special refrigeration equipment to achieve. Generally, the technical conditions on construction sites can meet this temperature requirement.

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