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Research Article

Temperature Control and Crack Prevention Measures for Concrete Ship Locks Subjected to Prolonged Casting Interruptions

Songhui Li, Xiangyu Luo, Guoxin Zhang, and Yi Liu

China Institute of Water Resources and Hydropower Research, Beijing 100038, China

Correspondence should be addressed to Xiangyu Luo; xy_luo@sina.cn

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During the construction of concrete ship locks, prolonged interruptions between the casting of the floor and lock wall are inevitable. In terms of mass concrete, long placement delays are one of the major reasons for the presence of cracks in newly placed concrete. Therefore, this study examines both the placement and structural characteristics of ship locks after long casting interruptions based on the mass concrete thermal stress theory to determine the major causal factors for cracks in newly poured concrete. Specifically, a block placement method is proposed to reduce thermal stress in newly placed concrete, and the temperature control and crack prevention capacities of the proposed method are verified using the finite element method. The development of the structure's thermal stress under different temperature control measures is analyzed, finding that thermal stress in the lock walls can be effectively reduced by 50% through low-temperature block casting. The results demonstrate that the proposed method can significantly reduce the internal thermal stress of newly placed concrete after prolonged casting interruptions, thereby highlighting its applicability for achieving effective temperature control and crack prevention in concrete ship locks.

1. Introduction

Ship locks are essential navigable structures in natural rivers or dam buildings, which usually comprise lock chambers, lock heads, lock gates, approach channels, and related equipment. Presently, ship locks are mostly constructed with reinforced concrete and are attached to massive thin-walled concrete structures. As observed from the construction procedures, structural characteristics and material characteristics of ship locks, temperature control, and crack prevention are key but challenging issues when constructing ship locks [1–3]. In a previous study, a finite element model of a concrete body was established to examine the viability of preventing thermal cracking by controlling the maximum temperature of concrete [4]. Another study analyzed the hydration heat in the pipe cooling system of concrete structures to predict the temperature of the concrete and cooling water to prevent cracking [5]. Although the need for strict temperature control measures to prevent cracks is widely recognized, in practice, vertical cracks often appear in structures such as lock walls, floors, and lead angles, rendering the repair of cracks that are discovered after construction as the only alternative, which can impact the safe operation and economic benefits of the walls [6, 7].

Preventing cracks when constructing structures such as lock walls and lead angles is a critical but difficult challenge. In a previous study, a statistical analysis was performed considering an interruption of more than 28 days between the placement of the lock chambers' floor, lead angle, and lock walls [8]. It is well known that prolonged interruptions remain the greatest concern in massive concrete placement. However, when considering construction techniques for ship locks, prolonged interruptions between the placement of the floor, lead angles, and lock walls are inevitable [9, 10]. Statistical analysis has shown that the shortest delay between placing the lock chamber floor and preparing the lock wall formwork is 40 days, with the usual delay between the placement of the floor and lock wall exceeding 60 days [11–13]. According to mass concrete temperature control theory, a long interruption during the placement of ship lock components will inevitably produce strong constraints on the lock walls. Additionally, a 28-day period leads to a higher temperature difference between new and old concrete [14]. The two unfavorable factors mentioned above are the reasons for cracking along the lock wall adjacent to the floor. These cracks can easily be flooded and facilitate hydraulic fracturing under lock wall weight and water pressure during future operations, thereby affecting the structure's overall safety. Based on construction experience, some ship locks were originally constructed using dense reinforcement to prevent these cracks [15–17]. However, practical engineering has demonstrated that, despite increased reinforcement ratios providing a certain crack-limiting effect, this effect is weak in lock walls experiencing prolonged casting interruptions. Reliable methods to prevent cracking along lock walls caused by a prolonged interruption between the lock wall and floor placement are still lacking. Instead, the existing solutions involve scheduled maintenance to repair existing cracks and provide further reinforcement [18].

Many scholars and experts have analyzed and studied the crack mechanism in lock walls or guide angles. It is mainly believed that cracks are caused by temperature stress. A previous study proposed a method for predicting the temperature distribution across mass concrete structures based on a finite difference model and the Arrhenius maturity function [19]. Several research models have been established to predict temperature progression in mass concrete structures, including the graphical method, Portland Cement Association method, Schmidt method, and finite element difference method [20]. The causes of cracks in ship locks have been examined in previous studies. It is generally believed that the temperature control standard and corresponding measures for concrete ship locks are the key factors for preventing cracks during construction; however, cracks still develop after the implementation of corresponding temperature control standards and measures [21]. For ship lock construction, the concrete specification for water transportation is specified, but no requirement is stipulated for the temperature difference between new and old concrete [16]. The finite element method is used to predict temperature distribution across mass concrete, quantify the maximum allowable internal temperature difference before cracking, and control cracks in practical engineering cases [22]. Some scholars have also explored temperature control measures, including insulation, to mitigate thermal stress [23–25]. Many engineering projects have employed steel bar densification or strengthening to prevent the occurrence of cracks. However, existing research suggests that, while steel bars may limit crack propagation, their effectiveness in preventing crack formation is rather limited [26, 27]. Furthermore, ship locks and other concrete structures exhibit adiabatic temperature rise characteristics, hindering the control of temperature differences between new and old concrete. Abundant simulation analysis methods and theoretical research exist on temperature stress; however, the meso-mechanism of cracks in fresh concrete caused in ship locks by prolonged casting interruptions is still unclear. Therefore, the factors that affect temperature stress after a prolonged concrete casting interruption must be evaluated. Appropriate temperature control measures and schemes are needed for crack prevention in new concrete in ship locks due to prolonged pouting delays.

This study examined the internal causes of cracking after a prolonged interruption from the perspective of concrete placing and hardening law. In particular, we investigated a block placement method that reduces thermal stress after a prolonged interruption and used the finite element method for verifying the proposed method's capacity to control temperature and prevent cracks. Therefore, this work provides a theoretical reference for temperature control and crack prevention in newly placed concrete after prolonged casting interruptions.

2. Thermal Stress Computation and Analysis

The cracks formed in newly placed ship lock concrete after a prolonged concrete placement interruption are mainly due to the stress caused by a change in the material properties and temperature during the hardening process. Studies have demonstrated that the occurrence of concrete cracks is attributable to stress exceeding the tensile strength of concrete, which, in turn, is related to temperature differences and constraint conditions. Therefore, there are many factors responsible for the cracks caused by excessive stress in newly placed concrete after a prolonged pouring interruption. For instance, after a long casting delay, the elastic modulus of the old concrete is more than 30 GPa, which strongly constrains the newly placed concrete. In addition, the temperature of the old concrete tends to have stabilized after a prolonged interruption, which causes a large temperature difference between new and old concrete [28]. The internal causes of these two cracking mechanisms in newly placed concrete are specifically analyzed in this section.

2.1. Thermal Stress Analysis after a Prolonged Concrete Casting Interruption. Prolonged interruptions between the placing of the ship lock floor and the vertical wall are inevitable. The floor's elastic modulus increases after a prolonged delay, and the temperature tends to be close to that of air after a long-term temperature drop. This increases the constraint imposed by the floor on the vertical wall and the temperature difference between old and new concrete, thereby leading to excessive stress that causes cracking along the vertical walls near the floor [22, 28].

After an extended pouring interruption, the hardening process of old concrete is almost complete. According to the evolution of concrete elastic modulus with time shown in Figure 1, the elastic modulus can reach at least 90% of its final value over 90 days. Therefore, placing new concrete after a similar period is equivalent to placing new concrete on a rigid bedrock [29].

According to Figure 1, the boundary condition for a structure subjected to a prolonged concrete casting interruption is as follows:

When $y = 0$, $v = 0$, and $\varepsilon_x = \frac{1}{E}(\sigma_x - \mu\sigma_y) + \alpha T$.

When $y = \mathrm{b}$, $\sigma_y = 0$, and $\tau_{xy} = 0$.

When $x = \pm\, \mathrm{a}$, $\sigma_y = 0$, and $\tau_{xy} = 0$.

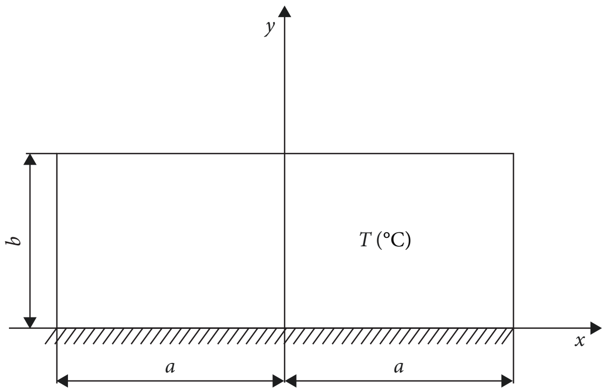

Figure 1: The diagram of concrete constrained by the bottom.

According to Zhu [1], thermal stress analysis of the newly placed block during uniform cooling on a rigid foundation leads to the corresponding stress solution in Equation (1).

$$\phi = \sum_{n=1}^{\infty} \frac{1}{\alpha^2{}_n} [A_n ch\alpha_n y + \alpha_n y B_n sh\alpha_n y + C_n sh\alpha_n y + \alpha_n y D_n ch\alpha_n y] \cos \alpha_n x. \quad (1)$$

We can obtain the following expression based on the stress solution equation.

$$\sigma_x = \frac{\partial^2 \phi}{\partial y^2} = \sum_{n=1}^{\infty} [(A_n + 2B_n + \alpha_n y D_n) ch\alpha_n y + (C_n + 2D_n + \alpha_n y B_n) sh\alpha_n y] \cos \alpha_n x. \quad (2)$$

The equation can be used to solve the shear stress of the two ends of the concrete block by substituting the boundary conditions into Equation (2) and referencing the solution of the short side of a rectangular plate under arbitrary loads. Therefore, the lateral stress of the concrete block can be solved using Equation (3).

$$\sigma_x = -\zeta \cdot E \cdot \alpha \cdot T, \quad (3)$$

where σ_x is the lateral stress of the vertical wall (tension is positive and compression is negative), ζ is the stress coefficient, and its value is given in Figure 2 (e) is the elastic modulus of the floor, α is the linear expansion coefficient, and T is the temperature difference between the vertical wall and the floor.

When considering the interval between the new and old concrete, Equation (3) can be expressed as follows:

$$\sigma_x = -\zeta \cdot E(\tau) \cdot \alpha \cdot T, \quad (4)$$

where ζ is the stress coefficient, which can be expressed as follows:

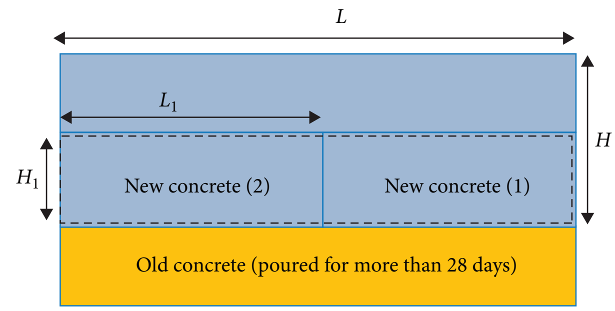

Figure 2: Schematic of layered and blocked calculation and analysis.

$$K_f = \frac{1}{1 + \frac{A_g E_C}{A_F E_F}}, \quad (5)$$

$$K_R = \left(\frac{\frac{L}{H} - 1}{\frac{L}{H} + 10} \right)^{h/H}, \quad (6)$$

where H is the length of the concrete, L is the height of the stress point, A_g is the gross area of the concrete cross-section at the foundation plane, A_F is the area of the foundation or zone restraining contraction of the concrete (recommended maximum value is 2.5 A_g), E_F is the modulus of elasticity of the foundation or restraining element, and E_C is the modulus of elasticity of the mass concrete.

The term $E(\tau)$ is the elastic modulus of the old concrete when considering the interval.

The horizontal normal stress of the newly placed concrete with different aspect ratios ($H/L = 1$, 1/2, 1/4, 1/8) can be roughly calculated with the equation, as shown in Figure 2. The following can be observed from the figure.

After a prolonged casting interruption, the elastic modulus of the floor concrete increases and generates a 100% constraint on the newly placed concrete, and the stress coefficients at the bottom of each aspect ratio are all close to 1.0.

To evaluate the safety factor of engineering temperature stress, the corresponding layer height, and block length can be calculated based on existing parameters. Therefore, it can be calculated and analyzed based on the above equation to determine the layering height of the Protestant concrete blocks and the corresponding pouring length of the blocks after an extended interruption as follows:

$$\sigma = K_R \cdot K_F \cdot E \cdot \alpha \cdot \Delta T/(1 - \mu) \le \sigma_t/K, \quad (7)$$

$$H_1 \ge H \cdot \log \frac{\left(\frac{\sigma_t (1-\mu)}{K \cdot K_F \cdot E \cdot \alpha \cdot \Delta T} \right)}{\left(\frac{L/H-1}{L/H+10} \right)}, \quad (8)$$

$$L_1 \le \frac{\left(\frac{\sigma_t (1-\mu)}{K \cdot K_F \cdot E \cdot \alpha \cdot \Delta T} \right)^{h/H_1} + 2}{\left(\frac{\sigma_t (1-\mu)}{K \cdot K_F \cdot E \cdot \alpha \cdot \Delta T} \right)^{h/H_1} - 1} H_1, \quad (9)$$

where K is the safety factor, σ_t is the tensile strength, H_1 is the layer height, and L_1 is the block length.

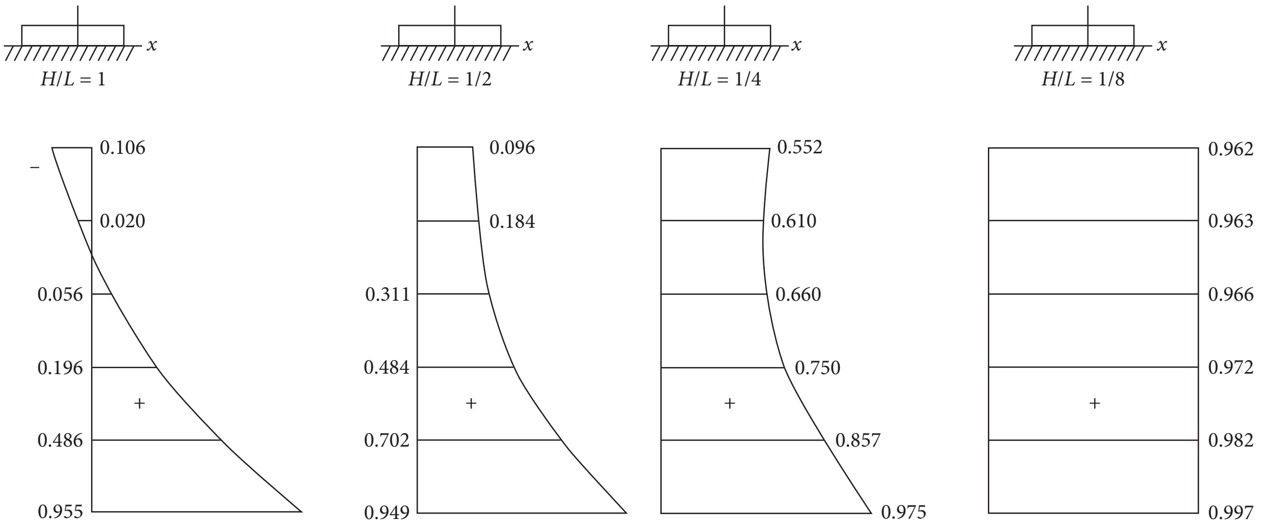

FIGURE 3: Thermal stress coefficient ζ during uniform cooling of the concrete block on a rigid foundation.

This method is mainly applied to the construction of thin-walled concrete for ship locks. Because the design phase of thin-walled concrete for ship locks does not consider the effect of stress increase caused by real environmental conditions such as prolonged casting interruptions, this method can accurately determine the height and length of layered and block pouring, which is conducive to on-site temporary plan changes and temperature control and crack prevention. It can improve the quality of concrete engineering without affecting the construction time on site.

The aspect ratio has a significant effect on the stress of the floor area that is close to the newly placed concrete. When the aspect ratio is 1/8, the entire cross-section coefficient is close to 1.0. When the aspect ratio is 1/2, the stress coefficient decreases with an increase in the wall height. When the aspect ratio is 0.7 H or below, it is tension stress; otherwise, when the aspect ratio is 0.7 H or above, it is compression stress.

By changing the aspect ratio, the stress distribution during the temperature drop of the newly poured concrete can be significantly changed.

It can be observed from Equation (4) that the horizontal normal stress of the newly placed concrete after a prolonged interruption is subjected to several factors. These include the stress coefficient ζ, the elastic modulus of the old concrete E, the linear expansion coefficient α, and the temperature difference T between the vertical wall and floor. Usually, the linear expansion coefficient is fixed. Therefore, the foremost strategies applied to reduce stress include decreasing the elastic modulus, the temperature difference between the new and old concrete, and the stress coefficient.

According to Equation (2) and Figure 3, there are two main approaches to reducing the thermal stress of the newly poured concrete after a long delay. These include reducing the thermal stress by increasing the aspect ratio and decreasing the temperature drop value to achieve temperature control and crack prevention for the newly placed concrete.

2.2. Analysis Method and Theory. This study used the independently developed SAPTIS software program [30] to simulate and analyze the ship lock floor and lock wall placement based on the analysis in Section 2.1. The simulation analysis process can reflect the material parameters, time characteristics, and temperature change law of the concrete in real-time during the concrete hardening process according to the actual placement process. Therefore, the calculated stress value is consistent with the actual engineering and can accurately reflect the material stress law after an extended concrete pouring interruption. As a result, the simulation can determine the most effective method to reduce the stress value after a prolonged delay.

The strain increment of the concrete under complex stress conditions usually includes elastic, creep, temperature, shrinkage, and an autogenous volume strain increment. Therefore, the strain increment that is produced in $\Delta\tau_n$ is expressed as follows:

$$\{\Delta\varepsilon_n\} = \{\Delta\varepsilon_n^e\} + \{\Delta\varepsilon_n^c\} + \{\Delta\varepsilon_n^T\} + \{\Delta\varepsilon_n^0\} + \{\Delta\varepsilon_n^s\}, \quad (10)$$

where $\{\Delta\varepsilon_n\}$ is the concrete strain increment, $\{\Delta\varepsilon_n^e\}$ is the elastic strain increment, $\{\Delta\varepsilon_n^c\}$ is the creep strain increment, $\{\Delta\varepsilon_n^T\}$ is the thermal strain increment, $\{\Delta\varepsilon_n^0\}$ is the autogenous volume strain increment, and $\{\Delta\varepsilon_n^s\}$ is the creep strain increment.

By integrating the physical, geometry, and equilibrium equations, the overall equilibrium equation is presented as follows:

$$[K]\{\Delta\delta_n\} = \{\Delta P_n\}^L + \{\Delta P_n\}^C + \{\Delta P_n\}^T + \{\Delta P_n\}^0 + \{\Delta P_n\}^S, \quad (11)$$

where $[K]$ is the concrete stiffness matrix of the R area, $\{\Delta\delta_n\}$ is the displacement increment of all the nodes in three

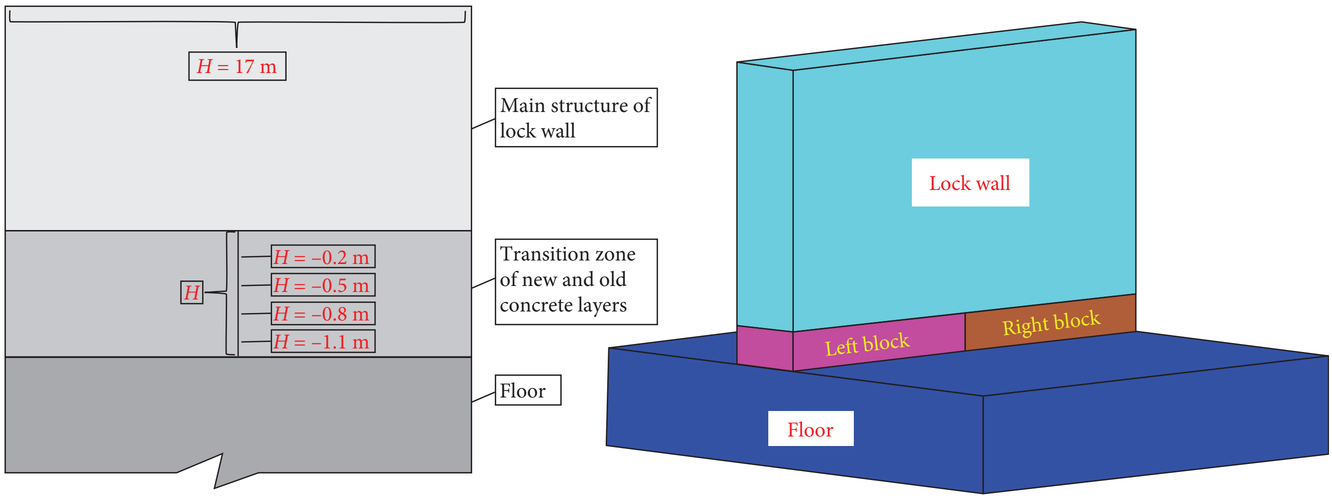

Figure 4: Schematic of the numerical model used to examine block concrete placement after prolonged casting interruptions.

directions in the R_i area, $\{\Delta P_n\}^L$ is the nodal load increment due to the external load, $\{\Delta P_n\}^C$ is the nodal load increment due to the creep strain, $\{\Delta P_n\}^T$ is the nodal load increment due to the temperature change, $\{\Delta P_n\}^0$ is the nodal load increment due to the autogenous strain, and $\{\Delta P_n\}^S$ is the nodal load increment due to the shrinkage strain.

3. Numerical Model and Operating Conditions

This study used a ship lock chamber as a study case to calculate and analyze the effects of prolonged interruption on the progression of thermal stress across newly placed concrete. This study also evaluated the effects of increasing the aspect ratio and reducing the temperature difference between the new and old concrete on thermal stress. The simulation was verified via numerical calculations using the concrete simulation analysis software SAPTIS, which was developed by Guoxin Zhang.

3.1. Numerical Model. The numerical model of this study is as follows: the length of the lock chamber is 17 m, and the first layer of concrete is 1–2 m thick. The key to achieving a segmented placement is to segment the first layer of the concrete, which increases the aspect ratio. The calculation model and diagram are shown in Figure 3. Excessive stress mainly occurs along the concrete's first layer. Therefore, we set four thermal stress monitoring points, as shown in Figure 4.

3.2. Computational Parameters and Operating Conditions. The concrete model adopted in this study is completely based on the actual construction process and intermittent period, and the corresponding material aging characteristics are fully considered for the material parameters of concrete.

(1) Exponential expression of age-related parameters as follows:

$$\theta(\tau) = \theta_0\left(1 - e^{-\alpha\tau^{\beta}}\right), \tag{12}$$

where τ is the age of the concrete, θ_0 is the age-related parameter (strength, elastic modulus, adiabatic temperature rise, etc.), and α and β are determined through tests and are used to describe the parameters of the heat rate of hydration.

(2) Expression of equivalent age considering the hydration degree as follows:

$$\tau_e = \int_0^{\tau} \exp\left[\frac{E}{R}\left(\frac{1}{273 + T_R} - \frac{1}{273 + T(\tau)}\right)\right] d\tau, \tag{13}$$

where $E/R = 4{,}000$–$5{,}000$ K, T_R is the reference temperature, 20°C, and $T(\tau)$ is the temperature of the concrete at time τ [31].

Calculate the concrete hydration degree τ_e from Equation (13). After using τ_e (equivalent age), substitute τ to obtain the equation for concrete hydration.

Ship lock concrete has a high adiabatic temperature rise, elastic modulus, and linear expansion coefficient. The computational parameters in this study are presented in Table 1.

In this study, finite element software was used to simulate the hardening process of concrete in the entire life cycle and the temperature field and stress field in different pouring processes. The stress characteristics of concrete under different working conditions are accurately evaluated based on the actual pouring process and the intermittent period of the lock wall.

In the operating conditions of this study, the intervals between the placement of the floor and the new concrete were 60 days. Different operating conditions were established to analyze the effects of the layered or block placement and that of the temperature difference reduction between the new and old concrete on the stress reduction of the newly placed concrete. The simulation analysis includes four operating conditions, as presented in Table 2. These are thermal stress analysis of newly placed concrete after a prolonged interruption (operating condition 1), thermal stress analysis of layered placing of new concrete after a prolonged interruption (operating condition 2), thermal stress analysis of layered and block placement of new concrete after a prolonged interruption (operating condition 3), and thermal

Table 1: Basic computational parameters of the concrete.

Adiabatic temperature rise (°C)	Elastic modulus (GPa)	Volume weight (ton/m^3)	Linear expansion coefficient (10^{-6}/°C)	Poisson's ratio
$T = 48.78\ (t - 0.30)/(t + 0.0683)$	$E = 44.8 \times (1 - \exp(-0.5\ t^{0.6}))$	2.45	0.874	0.167

Table 2: Operating conditions for the computation.

Conditions	Placing temperature (°C)	Spacing of pipes	Water temperature (°C)	Silo surface insulation
Condition 1	25	1.0 m × 1.0 m	20	One-time placement
Condition 2	25	1.0 m × 1.0 m	20	Layered placement
Condition 3	25	1.0 m × 1.0 m	20	Placing by dividing the first layer of the concrete into two blocks
Condition 4	15	1.0 m × 1.0 m	15	Insulate the floor; equivalent heat release coefficient is 2.92 kJ/(m^2 h °C)

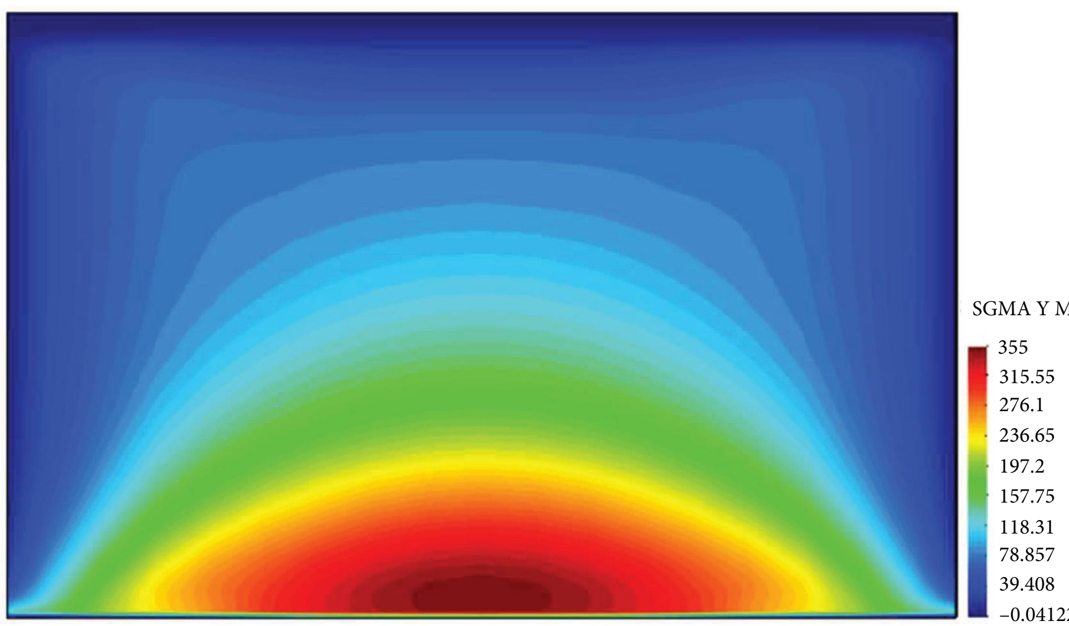

Figure 5: Thermal stress distribution for one-time placement.

stress analysis of the reduction in temperature difference T between new and old concrete after block placement of new concrete (operating condition 4). The techniques for reducing the temperature difference between the new and old concrete involve placing the new concrete at a low temperature, strengthening the cooling pipes, and insulating the old concrete.

4. Numerical Results and Analysis

4.1. Computational Simulation Results

4.1.1. Comparison of the Computational Result for Layered Placement. Because of a variety of reasons, such as the construction techniques for steel reinforcement [32, 33], during the placement of the lock wall, the excessive thickness of the newly placed concrete's placement layer will result in excessive temperature and thermal stress, as shown in Figure 5. Meanwhile, the lock wall is a thin-walled structure, and hence, it can cool down with its side during the placement, and the temperature field is not easy to control. Therefore, a thin layer of concrete needs to be set after a prolonged casting interruption to ensure a layered transition. This can significantly reduce the temperature difference between the new and old concrete and reduce thermal stresses, as shown in Figure 6.

The results presented in Table 3 indicate that the maximum and minimum values starting from the bottom of the one-time placement monitoring point are 3.5 and 3.39 MPa, respectively, whereas the maximum and minimum values starting from the bottom of the layered placement monitoring point are 3.18 and 2.65 MPa, respectively. The stress hydrograph is shown in Figure 7. The numerical simulation law of the layered and one-time placement is similar to that

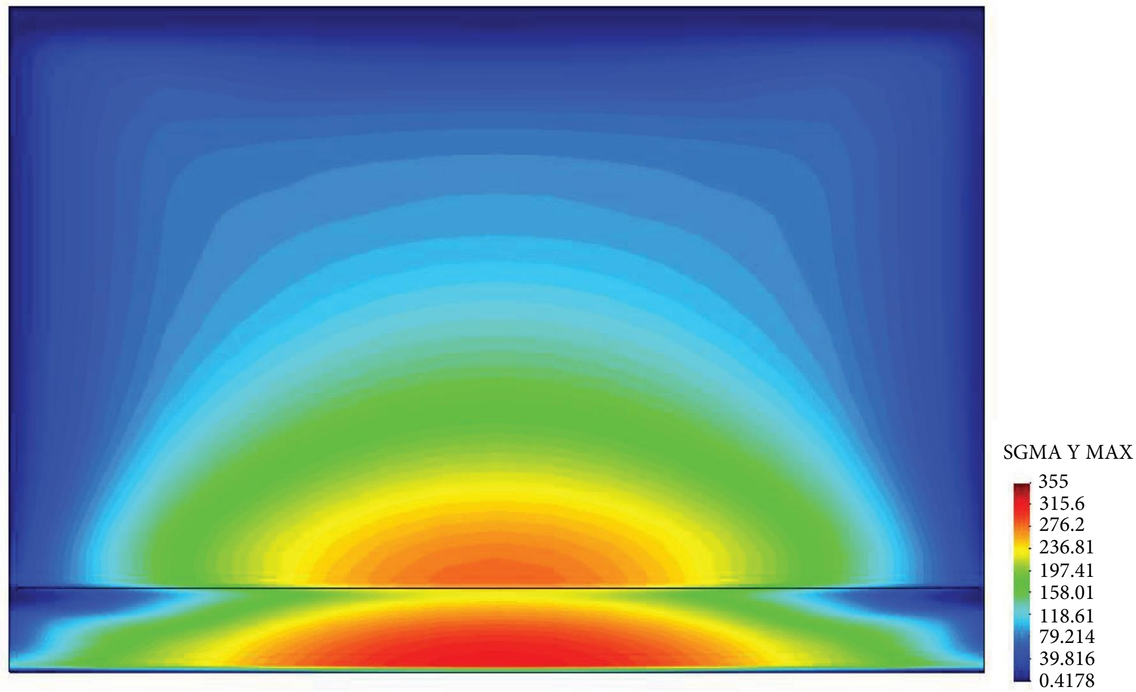

FIGURE 6: Thermal stress distribution for layered placement.

TABLE 3: Computational results of the thermal stresses of one-time placement and layered placement.

Operating condition	Maximum stress (MPa)			
	Monitoring point Elevation—1.1	Monitoring point Elevation—0.8	Monitoring point Elevation—0.5	Monitoring point Elevation—0.2
One-time placement	3.5	3.5	3.49	3.39
Layered placement	3.18	3.11	2.94	2.65
Stress differences	0.32	0.39	0.55	0.74

shown in Figure 3. In the same elevation range, the farther the distance from the old concrete, the smaller the stress value and the larger the stress reduction value of the layered placement.

4.1.2. Results of the Layered and Block Placements. Based on the stratification of the thin-walled structures, such as the lock walls, the bottom stress was still relatively large. According to the analysis in Section 2.1, the thermal stress at the bottom can be significantly decreased by reducing the aspect ratio and the temperature difference between the new and old concrete to prevent cracks. This study compared the computational results of operating conditions 2, 3, and 4 based on the above theory. It can be observed from a comparison of Figure 5 (one-time pouring), Figure 6 (layered pouring), Figure 8 (layered and block pouring), and Figure 9 (layered and block pouring and reduced temperature difference between the new and old concrete) that the use of layered and block placement reduces the temperature difference between the new and old concrete, which can significantly reduce the thermal stresses at the bottom of the newly poured concrete. The computational result of operating condition 4 shows that the maximum and minimum stress values at the bottom are 2.62 and 2.04 MPa, respectively (Table 4).

The effects of the different measures on reducing the stress values are different. It can be observed from a comparison of the thermal stress process lines of operating conditions 2, 3, and 4 (Figure 10) that the maximum and minimum differences between operating conditions 2 and 3 at the bottom are 0.49 and 0.38 MPa, respectively. The maximum and minimum differences between operating conditions 3 and 4 are 0.18 and 0.12 MPa, respectively. The differences between operating conditions 3 and 4 are significantly smaller than those between operating conditions 2 and 3.

4.2. Analysis of the Results. An analysis of the results indicates that the key factors include the basic elastic modulus and the temperature difference between the new and old concrete. Accordingly, it can be demonstrated from Equation (2) that the main methods for reducing stress involve decreasing the stress coefficient ζ, elastic modulus $E(\tau)$, temperature drop T of the newly placed concrete, and the linear expansion coefficient. However, according to the actual placing

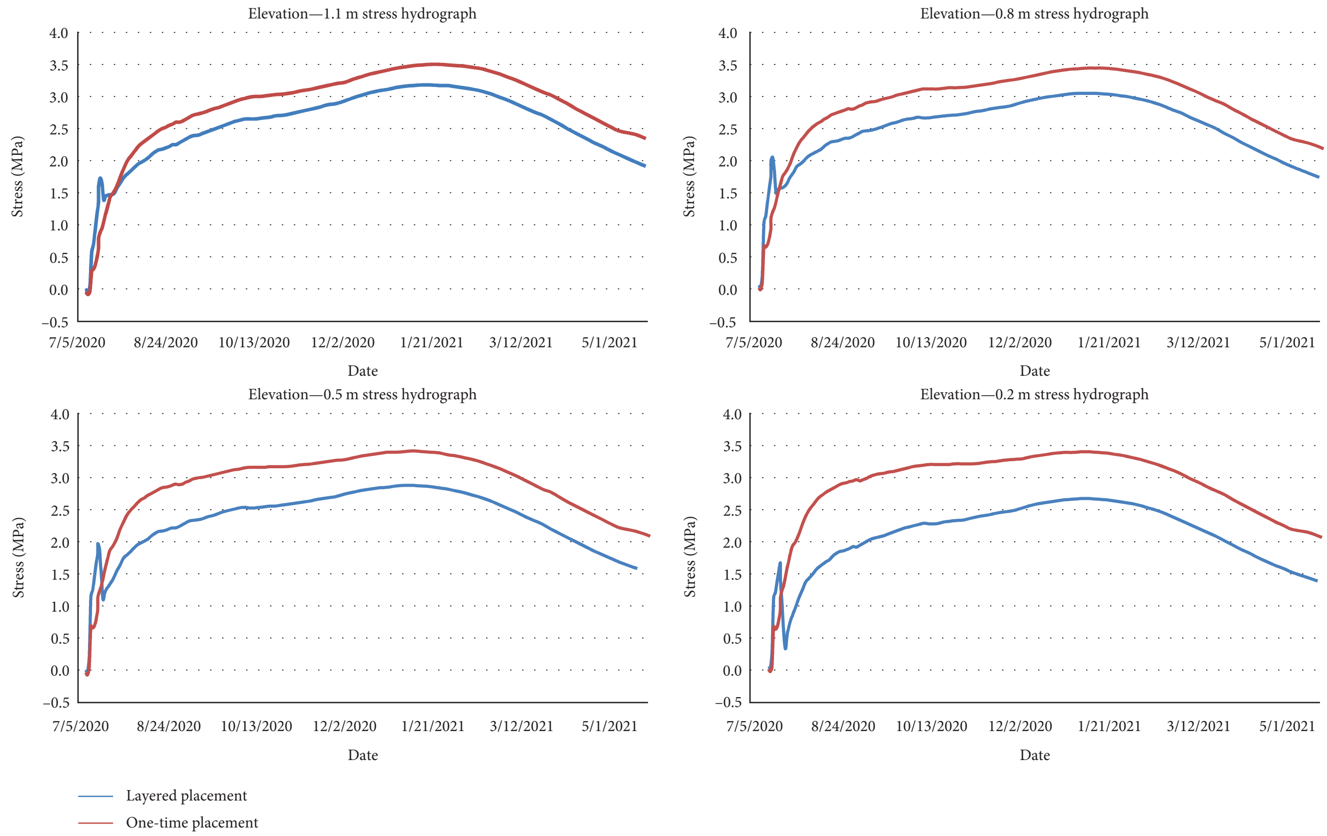

Figure 7: Stress process lines of one-time and layered placements at different operating conditions.

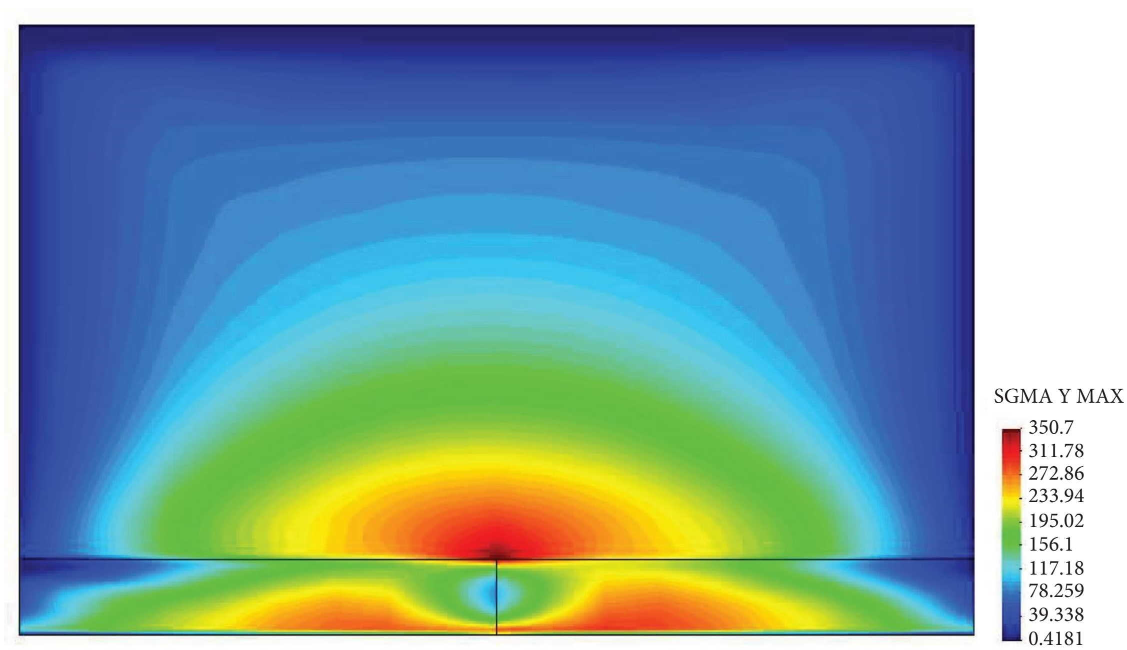

Figure 8: Maximum stress distribution for block placement.

conditions of the thin-walled concrete, a reduction in the linear expansion coefficient and elastic modulus $E(\tau)$ cannot be realized. Therefore, the main measures that can reduce the stress of the newly placed concrete involve decreasing the stress coefficient ζ and temperature drop T of the newly placed concrete. The specific measures are as follows: (1) according to the analysis in Section 2.1, block placement can increase the aspect ratio to reduce the stress coefficient

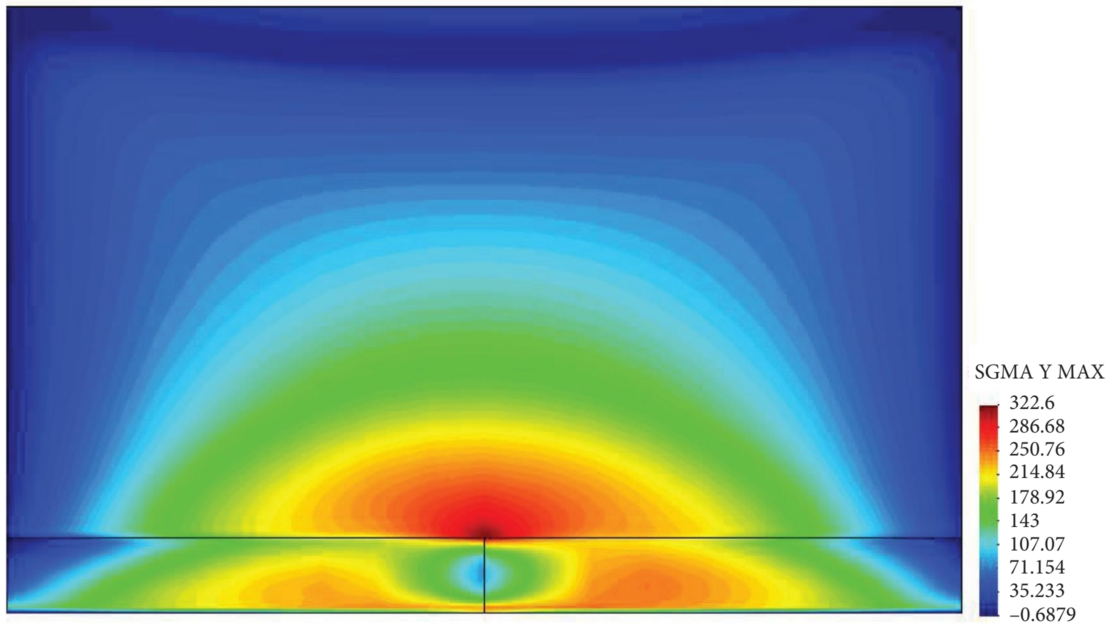

Figure 9: Maximum stress distribution for block placement under controlled temperature.

Table 4: Computational results of the thermal stresses of layered placement and block placement.

Operating condition	Maximum stress (MPa)			
	Monitoring point Elevation—1.1	Monitoring point Elevation—0.8	Monitoring point Elevation—0.5	Monitoring point Elevation—0.2
Layered placement—no insulation	3.18	3.11	2.94	2.65
Block placement—no insulation	2.80	2.69	2.48	2.16
Block placement—insulation	2.62	2.51	2.32	2.04

ζ; (2) layered pouring of the new concrete can increase the heat release; however, low-temperature placement of the new concrete and strengthening of the pipe cooling can reduce the maximum temperature of the newly placed concrete. Insulating the old concrete to reduce heat loss can prevent the temperature of the old concrete from being too low.

A concrete mass is commonly restrained by the foundation, other structures, or previous lifts. Full restraint seldom exists in a structure and only at specific locations. The induced strain in a structure can be calculated using the restraint equation, modified by factors based on the geometry and relative internal stiffness of the structure, as well as the relative stiffness of the structure compared to the foundation. Reducing the stiffness of the structure relative to the foundation and the temperature difference after a prolonged casting interruption is the key to crack prevention.

This study separately analyzed the effects of layered placement, block placement, and strengthening cooling on the stress values of the newly placed concrete. The effects of the three methods are summarized in Figure 11. The main findings are presented below.

Layered placement can significantly reduce the thermal stress of the newly placed concrete that is adjacent to the old concrete. The reduction in the thermal stress that is close to the old concrete is smaller and generally increases upward. The main effects of layering include reducing the thermal stress of the newly placed concrete that is at a distance from the old concrete. In addition, the effects are not significant for the area where the new and old concrete are in contact. The thermal stress reduction between the contacting areas of the new and old concrete is not significant, and the cracks of the newly placed concrete cannot be avoided.

The distribution characteristics of the thermal stress reduction for the block placement of the new concrete are similar to those for the layered placement. However, the computational results indicate that the thermal stress reduction effects of the block placement are more significant, particularly for the contacting areas of the new and old concrete, where thermal stress is significantly reduced. According to practical investigations, many cracks in the lock walls are generated at the bottom of the new concrete, and they extend upward. Therefore, block placement can significantly reduce the risk of cracking of the newly placed concrete.

Insulating old concrete to reduce the temperature difference between the new and old concrete can reduce the thermal stress of the newly placed concrete. The difference in the reduction between the contacting area and an area that is at a

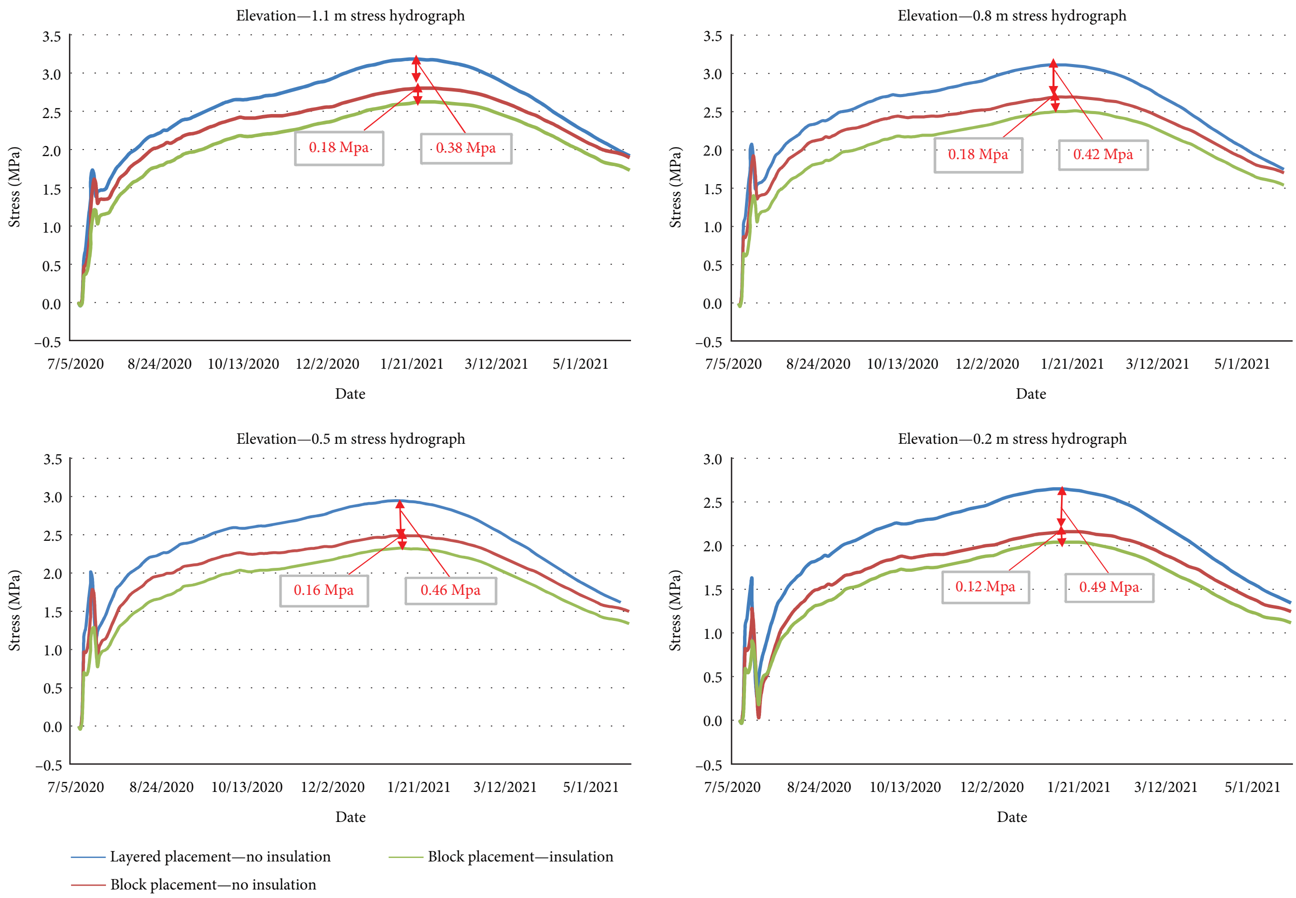

Figure 10: Comparison of the stress process lines at different elevations.

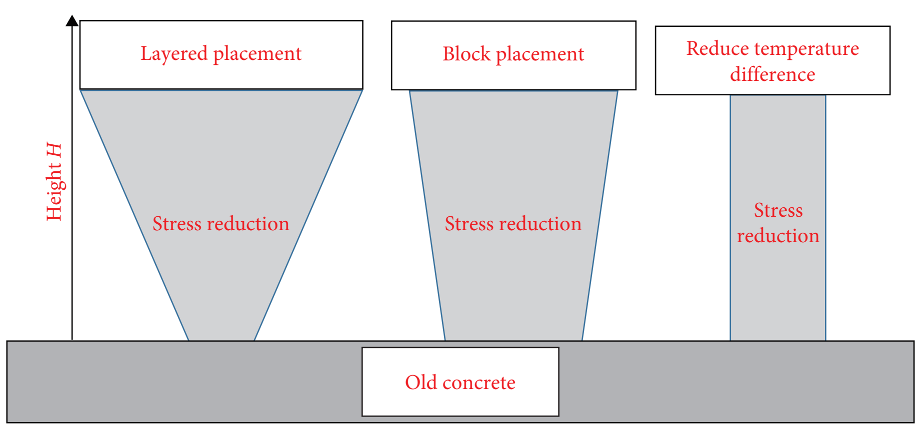

Figure 11: Stress reduction diagram of the different concrete placement methods.

distance from the contacting area is small. Meanwhile, the reduction is only 3% of the original stress, indicating that it has a small effect on stress reduction. Therefore, the effects of thermal stress reduction are lower than those of layered and block placement.

This study discovered and elaborated on the presence of at least one crack in each gate wall due to long intermittent periods in practical engineering. The cracking mechanism was elucidated, and the corresponding temperature control and crack prevention measures were proposed. Taking the Baishan Shiplock Hub as an engineering practice, the construction was carried out in layers and blocks based on the actual size of the lock wall. The height of the layer was 80 cm, and the construction was divided into two blocks. The results show that this method was economically effective, and there were no cracks in the 22 lock walls of this ship lock caused by long intermittent problems. This verifies the accuracy of the analysis presented in this article.

5. Conclusions

This study investigated and analyzed the causes of cracks in concrete ship locks resulting from prolonged interruptions between concrete placements during lock wall construction. The following conclusions are drawn based on the study's findings:

(i) The prolonged interruptions between the concrete placement of the lock wall and the floor are unavoidable. The significant stress in the contact area between the newly placed lock wall and the previously cast floor due to prolonged interruptions can lead to cracks originating from the bottom of the newly placed concrete. Theoretical analysis indicates that reducing the constraint coefficient of the old concrete and minimizing the temperature difference between new and old concrete can mitigate thermal stress in the newly placed concrete after a prolonged delay.

(ii) Layered and block placement methods are shown to substantially decrease the constraint coefficient and thermal stress at the bottom of newly placed concrete, as per theoretical results. Insulation measures exhibit limited effectiveness in reducing the temperature difference between new and old concrete, which, in turn, has a lesser impact on thermal stress reduction. Therefore, layered and block placement are identified as primary methods for mitigating thermal stress in newly placed concrete.

(iii) Concrete ship locks typically have high strength and heat of hydration. Methods for reducing the temperature difference between new and old concrete, such as insulating the old concrete and cooling the newly placed concrete, have limited efficacy in diminishing this temperature disparity. Consequently, reducing the temperature difference between new and old concrete proves less effective in reducing the thermal stress in newly placed concrete.

(iv) Currently, lock walls are typically completed in a single casting after a prolonged interruption. To prevent vertical cracks at the bottom of newly placed concrete, layered and block placement techniques are recommended. Moving forward, further investigation through practical means will be undertaken to explore the efficacy of layered and block placement techniques in preventing cracks in lock walls' newly placed concrete after prolonged casting interruptions.

Data Availability

The authors confirm that the data supporting the findings of this study are available within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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