Study on constraint degree calculation of frozen shaft inner wall mass concrete

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Abstract. Based on the circle-shaped air shaft of Hong Qing-He coal mine located in Inner Mongolia China, the thermal-mechanical numerical model of frozen shaft inner wall mass concrete was established under complex thermal-mechanical boundary, including internal heating, external cold source, friction constraints, above shaft load and lateral pressure. The evolution characteristics of temperature-displacement field of inner wall were analysed. According to numerical simulation results, the constraint degree at the middle section of inner wall concrete is calculated. In the early stage (0-10d), the constraint degree of inner wall fluctuates within 60-99% as curing time goes. Three protection measures to delete confinement degree of mass concrete shaft wall were proposed, including (1) Reducing the friction between inner and outer walls; (2) Reducing hydration heat release of mass concrete; (3) Reducing the temperature difference between inner and outer walls during curing.

1. Introduction

Coal production areas of China has been transferred from the eastern region to the western region after 2000. The main stratum in the western region of China is Cretaceous and Jurassic, and its characteristics are low compressive strength, soften by water and easy to weather. Therefore, it is hard to build shaft by conventional shaft sinking method. Artificial ground freezing (AGF) is an effective method to prevent water burst and large deformation in above stratum during shaft sinking [1]-[4].

However, the thickness of inner wall of freezing shaft increases gradually with the depth reach to 1000m, and it will exceed 2m according to current standards. High strength concrete often be used as a main method to reduce inner wall thickness, but early temperature-constrained crack often emerges after curing under low-temperature environment because this kind concrete is higher hydration exothermic than ordinary concrete [5]. Early temperature microcracks would expansion, penetration and cracking gradually with the shaft load and hydraulic pressure increases after frozen wall thawing. The shaft structure will unstable and damage if most of temperature microcracks propagation because inner shaft structure is the last sealing water and anti-pressure structure.

Several previous studies have investigated mechanical properties of shaft concrete under high hydraulic pressure, freezing shaft wall structure of deep bedrock and the mechanism of disruption of shaft in the epipedon [6]-[9]. Most of their results seldom consider the impact of early temperature
stress on confinement degree of shaft wall under complex thermal-mechanical boundary, such as internal heating, external cold source, friction constraints, above shaft load and lateral pressure. Above problem is one of the most important issue of freezing shaft stability study.

Here, we report a novel numerical simulation method that considers complex thermal-mechanical boundary to grasp the change of early temperature stress and calculate relating confinement degree of inner wall. This enables us to determine how to delete confinement degree of mass concrete shaft wall and propose relevant protection measures.

2. Project overview
The circle-shaped air shaft of Hong Qing-He coal mine located in Inner Mongolia, which diameter and depth are 7.6m and 689m respectively. The main stratum is Quaternary, Cretaceous (534.23m) and Jurassic (390.32m). A schematic diagram of the frozen shaft is shown in Fig.2, the shaft consists of outer wall, plastic plate and inner wall. Based on the design documents, the thickness of frozen wall is 3.7m, the lowest saline temperature is -28~ -32℃and the average temperature is not higher than -10℃. In this study, the C70 inner wall of shaft at -440~ -636m are selected as a prototype, which thickness is 1.2m can be treat as mass concrete.

![Fig.1 shaft structure and frozen wall of Hong Qing-He coal mine which consist of (1) outer wall, (2) plastic plate, (3) inner wall, (4) freezing hole, (5) frozen wall](image)

3. Model description of numerical simulation

3.1 Basic assumptions
Considering the actual physical process, some basic assumptions are introduced as below: (1) outer wall, inner wall and frozen rock is homogeneous and can be treated as linear elastic material; (2) Concrete and rebar of inner wall is compatible deformation; (3) Temperature, stress and strain of cylinder-shaped satisfies spatial axisymmetric finite element model; (4) Frozen wall simplified as constant temperature cold source.

3.2 Governing equations
The solid heat transfer axisymmetric model is expressed as:

\[
\frac{\partial T_n}{\partial \tau} = \frac{\lambda_n}{c_n \rho_n} \left( \frac{\partial^2 T_n}{\partial r^2} + \frac{1}{r} \frac{\partial T_n}{\partial r} \right) + \frac{Q}{c_n \rho_n} \quad (r > 0, 0 < r < \infty)
\]

where \(T, \tau, c, \rho, \lambda\) and \(Q\) are temperature, time, specific heat capacity, density and hydration releases heat, respectively. Subscript \(n\) can be divided 1, 2 and 3 represent inner wall, outer wall and frozen wall. \(r\) is the distance between any point and innermost of inner wall.
The thermal stress axisymmetric model has been derived as below [10]:

\[
\begin{align*}
\sigma_r &= -\frac{\alpha_f E}{(1-\mu)r^2}\left[T_i r dr + D_1 + \frac{D_2}{r^2}\right] \\
\sigma_\theta &= -\frac{\alpha_f E}{(1-\mu)r^2}\left[T_i r dr - T_r r^2 \right] + D_1 - \frac{D_2}{r^2} \\
\sigma_z &= \mu(\sigma_r + \sigma_\theta) - \alpha_f ET_i \\
\tau_{r\theta} &= 0
\end{align*}
\]  

(2)

where \(\sigma_r\), \(\sigma_\theta\), \(\sigma_z\) and \(\tau_{r\theta}\) are radial, circular, vertical and tangential stress, respectively. \(D_1\) and \(D_2\) is undetermined coefficient. \(\alpha_f\) is coefficient of thermal expansion of inner wall. \(a\) is radius of inner wall. \(\mu\) and \(E\) are poisson ratio and elasticity modulus, respectively.

The confinement degree of inner wall can be calculated by below equation:

\[
k = \left(1 - \frac{L_c}{L_f}\right) \times 100
\]

(3)

where \(L_c\) and \(L_f\) are displacement under constraint and free conditions.

### 3.3 Physical parameters and boundary conditions

The numerical model presented in this study included the inner wall concrete pouring at 620 m and frozen wall. As is shown in Fig.2, A axisymmetric numerical model with a range width 4.3m × height 5 m, consisting of 0.5m outer wall, 1.2m inner wall and 2.6m frozen wall. Using the descriptions above, an axisymmetric numerical model consisting of 8,600 quadrilateral elements was created.

Physical parameters and boundary conditions at different stage as follow:

#### Table 1 Thermophysical parameters

| Materials    | Density / (kg·m⁻³) | Thermal conductivity/ (W(m·K)⁻¹) | Specific heat capacity / (kJ (kg·K)⁻¹) |
|--------------|--------------------|----------------------------------|----------------------------------------|
|              |                    | -20°C | 20°C | -20°C | 20°C |
| Stratum      | 2040               | 1.82  | 0.95 | 0.96  | 1.20 |
| Outer wall   | 2350               | 2.53  |      |       |      |
| Inner wall   | 2525               | 3.2   |      |       |      |

(1) The pre-pouring stage of the inner wall

The initial temperature of stratum is 26°C and outer temperature boundary of frozen wall is -20°C. The initial temperature boundary of inner wall can be grasped when the temperature of outer wall reach 0°C according to field monitoring. The physical and thermodynamics parameters for all materials are listed in Tables 1.

(2) The 0-10d poured stage of the inner wall
The heat convection between concrete surface of inner wall and air is inevitable during concrete poured stage and its transfer coefficient can be calculated by below equation [11]:

\[ N_u = 3.06v + 0.035\Delta t_2 + 9.55 \]  

(4)

where \( v \) is the speed of air usually 2m/d according to field measurement. \( \Delta t_2 \) is the temperature difference between concrete surface and air.

The internal heating of inner wall attribute to the hydration heat of cement in concrete. Three hydration heat of cement model has been proposed by Zhu et al, such as exponential, hyperbolic and compound exponentials. The adiabatic temperature rises of inner wall concrete deduced from hydration heat is expressed as [12]:

\[ \theta(\tau_i) = \frac{Q(\tau_i) \cdot (W + kF)}{c_i \rho_i} \]  

(5)

where \( Q(\tau_i) \) is cumulative hydration heat at \( \tau_i \), \( W \) is cementitious material consumption of per cubic meter concrete. \( F \) is mixed material consumption of per cubic meter concrete. \( k \) is reduction factor.

Using the descriptions above, the thermal boundary condition of inner wall is as follow: 1) the top and bottom boundary was set thermal insulation. 2) the left vertical boundary was set thermal flux and can be calculated by Eq. (2). 3) the right vertical boundary was set thermal contact which simulate heat transfer of plastic plate. 4) The initial temperature was set as 10\(^\circ\)C, and the hydration heat was calculated by Eq. (5).

Fig.3 Mechanical model of inner wall of (a) constraint model and (b) free model.

As is shown in Fig.3, the mechanical boundary can be divided constraint and free model. The in situ mechanical boundary is simplified as Fig.3 (a), the top boundary was set boundary load \( P_1 \), the left vertical boundary was set free, the right vertical boundary was set friction by plastic plate, the horizontal and vertical displacements of the bottom boundaries were constrained, the sum of surrounding rock pressure and frost heave force \( P_3 \) on outer wall was set as 2MPa based on the field monitoring data. The free model only constrains the horizontal and vertical displacements of the bottom boundaries.
4. Verification and analysis

4.1 Temperature field analysis

As is shown in Fig.4 (a), the middle temperature is obviously higher than other part in the inner wall. The main reason is that the heat conduction ability of concrete is so poor that the heat transfer in the middle part is hindered, but air and cold source exchange heat with inner and outer edge of inner wall continually in the meanwhile.

Based on the field monitoring data, the middle temperature of inner wall increased sharply to 70°C in 0 to 48h, and then dropped gradually (shown in Fig. 4(b)). The trend of temperature history calculated by three hydration heat of cement model is similar as field monitoring data, and compound exponential error is the minimum. Therefore, compound exponential is more suitable than other models on early hydration heat calculation of freezing shaft concrete.

4.2 Displacement field analysis
Fig. 5 shows that the evolution of displacement field of inner wall concrete in different periods. The concrete expansion at the early period (0-24h) with temperature increases leading to the maximum upward displacement 1.6mm, whereas the displacement decreases gradually as curing time goes. The displacement of inner wall goes down to negative at 360h because of concrete shrink and increased vertical load. Therefore, concrete expansion and shrink of inner wall is obviously during 0-15d.

4.3. Constraint degree analysis

As is shown in Fig.6(a), the maximum displacement at the middle section of inner wall under free condition is 1.2mm, while central and intervallum constrain are 0.4 and 0.038mm respectively. Obviously, the intervallum constrain is higher than central constrain leading to higher stress beside intervallum. The stress beside intervallum sharply increases as curing time goes and reach 2MPa finally (Fig.6(b)). Therefore, the cracking risk beside intervallum is higher than other area of inner wall.
The constraint degree beside intervallum at the middle section of inner wall concrete is calculated by Eq.(3) and shown in Fig.7. In the early stage (0-10d), the constraint degree of inner wall fluctuates within 60-99% as curing time goes, and two peaks in the curve emerge at the time of rapid temperature change. It is indicated that constraint degree is closely associated with the temperature change, and the cracking or damage risk time of inner wall in early-age curing is 0-10d.

In summary, the main relevant protection measures to delete confinement degree of mass concrete shaft wall as follow: (1) Reducing the friction between inner and outer walls; (2) Reducing hydration heat release of mass concrete; (3) Reducing the temperature difference between inner and outer walls during curing.

5. Conclusions
In this report, a numerical method for calculating predicting constraint degree of frozen shaft inner wall mass concrete was proposed. This proposed method is easily applicable in practical construction. Based on the novel method, the evolution characteristics of temperature-displacement field of inner wall were analyzed. The following conclusions can be drawn from the study:

(a) The thermal-mechanical numerical model of frozen shaft inner wall mass concrete is established under complex thermal-mechanical boundary, such as internal heating, external cold source, friction constraints, above shaft load and lateral pressure.

(b) The cracking risk beside intervallum is higher than other area of inner wall and the cracking or damage risk time of inner wall in early-age curing is 0-10d.

(c) Base on numerical simulation results, the constraint degree at the middle section of inner wall concrete is calculated. In the early stage (0-10d), the constraint degree of inner wall fluctuates within 60-99% as curing time goes.

(d) The main protection measures to delete confinement degree of mass concrete shaft wall as follow: (1) Reducing the friction between inner and outer walls; (2) Reducing hydration heat release of mass concrete; (3) Reducing the temperature difference between inner and outer walls during curing.

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