Numerical simulation of performance evolution of anti-seepage curtains in the high water head tunnel surrounding rock

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Abstract: To study the dynamic evolution process of the anti-seepage curtain under high water head, a multi-physics coupling model reflecting the time-effect of the curtain was established based on the principles of seepage mechanics, solute migration and chemical kinetics. The model is composed of a seepage model, a solute migration model, and a curtain dissolution model, which is solved by the finite element method, and verified by combining the relevant uplift pressure monitoring data. The simulation results indicate that the porosity of the anti-seepage curtain increased by 29.38% compared with the initial porosity, and the permeability coefficient increased by 1.95 times. The dissolution of the anti-seepage curtain had the characteristics of temporal and spatial variation, the dissolution extent at the middle part is much quicker than at its bottom part, particularly, there is almost no dissolution at its top part. The dissolution area near the upstream side of the anti-seepage curtain is larger than that on the downstream side. Simultaneously, the research results and monitoring data are available to evaluate the durability of the curtain, and provide a scientific basis for the safe operation and management of the power station.

1. Introduction

In order to rationally develop and utilize hydropower resources, China has built a number of large water conservancy and hydropower projects with huge scale and complex hydrogeology, among which
some types of high dams even reach 200–300m [1][2][3]. During the operation of the high dam, the seepage pressure of the dam foundation anti-seepage curtain is as high as 3MPa, and the seepage slope of the rock mass between the anti-seepage drainage system exceeds more than dozens, and the leakage problem is extremely prominent [4]. Because the anti-seepage curtain has been working in an environment of high water head and high seepage pressure for a long time, the water interacts with the rock and the anti-seepage curtain to dissolve, which weakens the anti-seepage performance of the anti-seepage curtain or even fails, which will have a serious impact on the stability and security of the dam [5]. In view of the specific problems caused by the performance evolution of the anti-seepage curtain under high water head, a reasonable optimization treatment plan is proposed, which is of great significance to the safe and stable operation of the hydropower station.

In recent years, the research on the anti-seepage performance of the anti-seepage curtain had mainly focused on hydrogeochemical basic theories and methods. Gao [6] and Chen [7] adopted two-dimensional seepage model to calculate the seepage flow, seepage field and seepage slope of the anti-seepage scheme, and optimized the anti-seepage scheme based on the calculation results. Huo [8] applied the hydrogeochemical graphic method to determine the anti-seepage performance of the dam foundation anti-seepage curtain and possible anti-seepage defects based on the characteristics of underground water quality behind the scenes. Liu et al. [9] calculated the permeability coefficient of the anti-seepage curtain of the dam foundation of Darcy's law expressed by the water chemistry index, and quantitatively analyzed the reliability of the curtain body. Peng [10] established a multi-field coupling model of water-rock-curtain interaction based on the theory of continuum dynamics and chemical kinetics to quantitatively evaluate the anti-seepage performance of the anti-seepage curtain. Zhang [11] established a permeation-coupling model based on chemical kinetics to determine the durability control index of the anti-seepage curtain, and therefore evaluate the anti-seepage performance of the anti-seepage curtain. However, there are relatively few studies on the anti-seepage performance of anti-seepage curtains in complex environments, especially the research on the timeliness of anti-seepage curtains under high water head and high seepage pressure conditions.

In order to study the dynamic process of the attenuation of the curtain's anti-seepage performance under the action of high water head, this paper couples the seepage model of the reaction seepage field, solute migration model of the chemical field with the anti-seepage curtain dissolution model, establishes a numerical analysis model, and uses the finite element method to solve the calculation. Obtain the visual process of the microstructure of the anti-seepage curtain over time, and verify it through engineering data to provide a basis for subsequent research.

2.Multi-physical field coupling model of the anti-seepage curtain for high-pressure tunnel
Based on the principles of continuum dynamics, solute migration and chemical dynamics, a multi physical field coupling model is established to describe the dynamic process of anti-seepage curtain performance evolution under high water head.

2.1 Seepage model
The anti-seepage curtain and the surrounding rock mass are equivalent continuous media, and the flow of groundwater in the porous media can be described by Darcy's law:
\[
\begin{align*}
\frac{\partial (\varepsilon_P \rho P)}{\partial t} + \nabla \left( \rho u P \right) &= Q_m \\
u &= -\frac{k}{\rho G} \nabla P
\end{align*}
\] (1)

Where: \( \varepsilon_P \) is the porosity; \( \rho \) is the pore water pressure; \( t \) is the time; \( \nabla \) is the gradient; \( \rho \) is the density; \( u \) is the seepage flow rate; \( Q_m \) is the source and sink term; \( k \) is the permeability coefficient.

The Kozeny-Carman equation is used to express the relationship between the permeability coefficient \( k \) and the porosity \( \varphi \) of the anti-seepage curtain [12]:

\[
k = \varphi^3 \left( 1 - \varphi^2 \right)^3 \left( 1 - \varphi \right)^{-1}
\] (2)

Where: \( k \) and \( \varphi \) are the permeability coefficient and porosity of the anti-seepage curtain in the initial state, respectively.

2.2 Solute migration model

The migration of the solute in the aqueous solution and the change in the solute concentration caused by the chemical reaction between the water and the anti-seepage curtain can be described by Fick's second law:

\[
\frac{\partial (\varphi C)}{\partial t} + u \nabla C + \nabla \left( -D \nabla C \right) = R_c
\] (3)

Where: \( C \) is the concentration of solute \( \text{Ca}^{2+} \) in groundwater; \( \varphi \) is the porosity of porous media; \( u \) is the Darcy flow velocity; \( D \) is the hydrodynamic dispersion tensor; \( R_c \) is the increase rate of \( \text{Ca}^{2+} \) in the solution.

The dispersion coefficient tensor \( D \) is mainly affected by the Darcy flow velocity, and its functional relationship satisfies the following equation:

\[
D_{ij} = \alpha_L u \delta + \left( \alpha_L - \alpha_T \right) \frac{u_i}{u} + D_m \tau
\] (4)

Where: \( \delta \) is the Kronecker function; \( u \) is the Darcy flow velocity; \( \alpha_L \), \( \alpha_T \) is the transverse dispersion coefficient and the longitudinal dispersion coefficient, \( D_m \) is the diffusion coefficient of \( \text{Ca}^{2+} \) in water, and \( \tau \) is the tortuosity of the porous medium [13].

\[
\tau = -1.5 \tan \left\{ 8.0 \left( \varphi - 0.25 \right) \right\} + 2.5
\] (5)

2.3 Dissolution model of anti-seepage curtain

The dissolution and loss of hydration products such as \( \text{Ca(OH)}_2 \) and calcium silicate hydrate (CSH)
will increase the porosity of the anti-seepage curtain. Due to the complex dissolution process of CSH gel, in order to simplify the model, the dissolution process of CSH gel is ignored and only the dissolution process of Ca(OH)$_2$ is considered. [14][15]. With the dissolution of Ca(OH)$_2$, the porosity of the anti-seepage curtain continues to increase, and its growth rate is related to the dissolution rate and molar volume of Ca(OH)$_2$ in the anti-seepage curtain. The following formula can be used [16]:

$$\frac{\partial \varphi_s}{\partial t} = M_s \cdot R_s \cdot \varphi_l$$  \hspace{1cm} (6)

Where: $M_s$ is the molar volume of Ca(OH)$_2$; $R_s$ is the dissolution rate of Ca(OH)$_2$.

The dissolution rate $R_s$ of Ca(OH)$_2$ is a function of the concentration of calcium ions $C$ in the solution, so the following relationship can be used [17]:

$$R_s = -k_d A \left(1 - \frac{Q}{k_{up}}\right) [C]^n$$  \hspace{1cm} (7)

$$k_{up} = 0.0125 \times 10^9 e^{-0.019T}$$  \hspace{1cm} (8)

Where: $k_d$ is the dissolution rate coefficient; $n$ is the index 3; $A$ is the specific surface area, which can be obtained by the BET nitrogen adsorption experiment; $Q$ is the adsorption density of solute ions adsorbed on the solid phase. The increasing rate of Ca$^{2+}$ in the solution is numerically equal to the dissolution rate of Ca(OH)$_2$ in the anti-seepage curtain, which is $|R_s| = |R_l|$.

2.4 Coupling process

Under the long-term erosion of high water head, the microstructure of the anti-seepage curtain changes, the porosity increases, and the permeability coefficient increases, which leads to an increase in the flow rate. The increase in the flow rate accelerates the precipitation process of calcium ions, thereby accelerating the dissolution process and forming a cyclical effects of mutual influence eventually lead to the continuous decline of the impermeability and durability of the anti-seepage curtain. The specific coupling relationship is shown in figure 1.
Figure 1. Model composition and coupling relationship

3. Engineering example analysis

3.1 Calculation model
Fujian Xianyou Pumped Storage Power Station has an installed capacity of 1200MW. The water delivery system is shown in figure 2, consisting of high-pressure bifurcated pipes, drainage corridors, faults, dense joints and anti-seepage curtain. The model mesh is finely divided, the element grid is shown in figure 3. Take 30a as the total time to simulate the dynamic process of the attenuation of the anti-seepage performance of the curtain under high water head.

![Figure 2. The geometric size of the model calculation area](image)

![Figure 3. Model finite element mesh quality diagram](image)

3.2 Calculation Parameters and Boundary Conditions
The actual range of the anti-seepage curtain is taken as the research object, and the hydrogeological parameters of the model are shown in Table 1. The upstream and downstream boundary conditions and reaction parameters of the model are shown in Table 2. According to the seepage monitoring data and on-site safety inspection data, the seepage monitoring data is used for back analysis to obtain the permeability coefficient of the material [18], and the initial porosity is given according to the empirical data.

| Medium type          | θ     | k(m/s)  | α(m)          | D_{d}(m^{2}/s) |
|----------------------|-------|---------|---------------|----------------|
| Anti-seepage curtain | 0.08  | 1.0×10^{-8} | 5(Horizontal) |               |
| Granite Porphyry     | 0.1   | 2.79×10^{-6} | 40(Vertical)  | 1×10^{-9}     |

| h_{d}(m) | h_{d}(m) | k_{d} | M_{d}(cm^{3}/mol^{-1}) | Q(kg/m^{3}) | T(K) |
|----------|----------|-------|------------------------|-------------|------|
| 703      | 220      | 3     | 33                     | 2400        | 298.15 |

3.3 Validation
Figure 4 is the comparison between the monitoring value of pore water pressure behind the scenes and the simulated value. The location of the pressure pipe is shown in figure 2. Two monitoring points P_1 (14 , 213.5) and P_3 (28 , 213.65) are enabled. The uplift pressure reduction coefficient of the two
monitoring points closest to the model water level from 2014 to 2019 is obtained by formula (9).

\[ \alpha = \frac{h_i - h_j}{h_s - h_x} \]  

(9)

In the formula: \( \alpha \) is the uplift pressure reduction coefficient, \( h_i \) - the measured water level at the point \( i \); \( h_s \) - the upstream water level; \( h_x \) - the bedrock elevation at the measuring point.

**Figure 4.** Evolution curve of uplift pressure reduction coefficient

It can be further observed from figure 4 that the calculation curve is in good fitting with the monitoring value fitting curve, which shows that this model can better reflect the decay process of the anti-seepage curtain's impermeable curtain performance.

4. Results and discussion

4.1 Movement law of seepage field

On the basis of the established multi-physics coupling model, the engineering calculation model is discretized, and the law of the anti-seepage curtain seepage field changing with time is revealed through software simulation analysis. For intuitive reflection, figure 5 shows the change of the permeability coefficient of the anti-seepage curtain behind a pumped storage hydropower station 30a; figure 6 shows the evolution of permeability coefficients of curtains with different elevations after 30a.

**Figure 5.** Variation of permeability coefficient of anti-seepage curtain with

**Figure 6.** Change Law of Permeability Coefficient of anti-seepage Curtain at Different Elevations after 30 Years
Figure 5 plots the change curve of the anti-seepage curtain permeability coefficient, it increases with the running time, and the anti-seepage curtain permeability coefficient increases to $1.95 \times 10^{-8}$ m/s after running for 30 years, which is the initial permeability coefficient ($1.0 \times 10^{-8}$ m/s) 1.95 times, indicating that the microstructure of the anti-seepage curtain has changed, and the anti-seepage performance is gradually declining. The increase rate of the permeability coefficient of the curtain on the upstream side is greater than that on the downstream side. At the bottom elevation of 168m, the evolution curve of permeability coefficient presents a "U" shape.

The change of the permeability coefficient of the anti-seepage curtain will cause the change of the seepage morphology. Selecting four points to compare the change of the seepage velocity in the anti-seepage curtain, the results are shown in figure 7.

![Figure 7](image_url)

**Figure 7.** Variation of groundwater velocity at different positions in the anti-seepage curtain

Figure 7 depicts that with the increase of the permeability coefficient, the velocity of each point on the center line of the anti-seepage curtain gradually increases.

4.2 Law of Solute migration Field

The cement stone in the curtain is easily dissolved and lost under the environment of high water head and high osmotic pressure, resulting in the decrease of the strength and impermeability of the anti-seepage curtain. It can be observed that the deterioration of the strength and impermeability of the anti-seepage curtain depends on the dissolution process of calcium hydration products. By analyzing the change of Ca$^{2+}$ concentration, the degree of dissolution of the anti-seepage curtain can be
quantitatively studied in space and time.

**Figure 8.** Calcium ion concentration distribution diagram in calculation area during operation time

According to figure 8 depicts, the concentration of \( \text{Ca}^{2+} \) on the downstream side of the curtain is higher than that on the upstream side. This result indicates that the change in the calcium ion concentration on the upstream side is caused by the diffusion effect, the change in the calcium ion concentration on the downstream side is caused by the convection effect, and the convection effect is greater than the diffusion effect. The change of \( \text{Ca}^{2+} \) concentration can quantitatively study the degree of dissolution of the curtain in space and time.

In order to further explore the diffusion trend of \( \text{Ca}^{2+} \) behind the curtain, three coordinate points \( d_1 \) (40, 234.65), \( d_2 \) (50, 234.65) and \( d_3 \) (60, 234.65) are selected in the same horizontal direction behind the curtain. The change of \( \text{Ca}^{2+} \) concentration at each point when it tends to be stable is shown in figure 9.

**Figure 9.** Calcium ion concentration distribution diagram behind the curtain

From the calculation curve of point \( d_1 \), it can be observed that the calcium ion concentration increases faster near the top of the anti-seepage curtain, and then decreases slowly. The calcium concentration of \( d_2 \) and \( d_3 \) will be similar to that of \( d_1 \), showing a slow downward trend.

4.3 The distribution law of the microstructure of the anti-seepage curtain

After the simulation, the porosity distribution of the anti-seepage curtain is shown in figure 10 and figure 11 below.
It can be further observed from figure 10 and 11 that over time, the Ca$^{2+}$ in the anti-seepage curtain continues to dissolve and lose, and the porosity gradually increases. However, this change is uneven in time and space. After 20 years of operation, different parts of the anti-seepage curtain showed different degrees of dissolution. The dissolution of the anti-seepage curtain mainly occurs in the following locations:

1) The porosity on both sides of the middle of the anti-seepage curtain is large, and the dissolution phenomenon is obvious. It shows that the dissolution of the anti-seepage curtain may be related to the groundwater pressure and seepage velocity. The dissolution area on the upstream side of the anti-seepage curtain is obviously larger than that on the downstream side. It shows that the hydrodynamic pressure near the upstream side is greater than the hydrodynamic pressure on the downstream side.

2) The dissolution at the bottom of the anti-seepage curtain is more obvious, and the dissolution area is smaller than the middle part. It is a kind of "surround type" dissolution. It is characterized by dissolution from the surface to the inside. The main reason for this phenomenon is related to the seepage movement of high-pressure water around the anti-seepage curtain.

5. Conclusion

1) Based on the principles of continuum dynamics, solute migration and chemical kinetics, a multi-physical field coupling model is established in this paper, and the dissolution failure law of the anti-seepage curtain under the coupling action of seepage field, chemical field and microstructure during actual operation is studied. Thereby, the change process of the physical and chemical properties of the anti-seepage curtain is more realistically reflected in time and space.

2) The anti-seepage effect of the anti-seepage curtain gradually weakens over time, mainly due to the loss of soluble substances such as Ca(OH)$_2$ and calcium silicate hydrate (CSH) in the anti-seepage curtain. The dissolution of similar substances causes the permeability coefficient and porosity of the
anti-seepage curtain to increase. The results show that: a. The direction of groundwater seepage affects the horizontal and vertical dispersion of Ca$^{2+}$ caused by the seepage and erosion of the anti-seepage curtain, which is the main influencing factor leading to the migration and enrichment of Ca$^{2+}$; b. The erosion and destruction of the anti-seepage curtain mainly occurs in the middle of the anti-seepage curtain and high pressure The contact part of the bifurcated pipe, and the bottom dissolution is mainly from the surface to the inside, and the dissolution area is smaller than the two sides of the middle part.

3) By comparing with the monitoring data and seepage data of the hydropower station, the simulation calculation results conform to its natural laws. The model can be applied to other working conditions, and the actual effect quantities can be compared to evaluate the anti-seepage performance of the anti-seepage curtain.

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