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Thermodynamic Analysis of Coupled Seepage and Thermal Conduction Effects in Earth-Rock Dams

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ABSTRACT

The stability of earth-rock dams is a critical factor in hydraulic engineering, directly impacting the safety of reservoirs and downstream regions. Seepage and thermal conduction, key physical processes influencing dam stability, are typically studied independently. However, as environmental changes become increasingly significant, the interaction between these processes—the coupling effect—cannot be overlooked. This paper delves into the coupled effects of seepage and thermal conduction in earth-rock dams, initially establishing a coupled control equation for the seepage and temperature fields. Subsequently, a numerical model for the seepage process under thermal conduction coupling effects is developed. Through precise simulation, this study aims to enhance the predictive capability of dam behavior under various environmental conditions, thereby providing a scientific basis for dam design and maintenance. The research identifies that existing models often neglect the impact of temperature on seepage characteristics and exhibit biases in parameter selection and boundary condition settings, leading to inaccurate simulations of dam behavior in complex environments. Therefore, the numerical model in this study, considering key parameters such as convective heat transfer coefficients, offers a more comprehensive assessment of the stability and functionality of earth-rock dams in real-world conditions.

1. INTRODUCTION

Earth-rock dams, as critical hydraulic engineering facilities, are directly related to the safe operation of reservoirs and the safety of downstream areas [1-5]. During the operation of earth-rock dams, seepage and thermal conduction are two fundamental physical processes. Traditional research has focused on the individual effects of seepage or thermal conduction, but in reality, these processes often affect each other [6, 7]. With the impact of global climate change, the influence of temperature changes on the seepage characteristics within earth-rock dams has become more apparent. Therefore, studying the coupled effects of seepage and thermal conduction is significant for ensuring dam stability and extending their service life [8-10].

Related research indicates that the interaction between the seepage field and temperature field inside earth-rock dams can significantly affect the physical and mechanical properties of the dam body [11, 12]. For example, temperature changes can affect the viscosity and fluidity of water, thereby altering seepage velocity and pressure distribution, which are crucial for the structural safety and functionality maintenance of the dam. Additionally, temperature changes in earth-rock dams can also lead to changes in material properties, such as expansion or contraction, which directly impact the structural integrity and durability of the dam [13-15]. Therefore, exploring this coupling effect not only enhances our understanding of the seepage mechanisms in earth-rock dams but also provides scientific guidance for dam design and maintenance.

However, despite the practical significance of research on coupling mechanisms, existing studies still have some deficiencies in theory and methodology. Current models often overlook the interaction between the temperature and seepage fields or simplify some key influencing factors in the simulation process [16-18], such as insufficient consideration of convective heat transfer, leading to inaccurate predictions of dam behavior under different environmental conditions [19-21]. Moreover, many studies use parameters and boundary conditions that are too idealized, differing from real operational environments, which limits the widespread application of the models and their predictive capabilities for actual effects.

The main research contents of this paper include two parts: firstly, a thorough analysis of the coupling mechanism between the seepage field and temperature field in earth-rock dams, establishing a hydrothermal coupling mechanism that includes coupled control equations for the seepage and temperature fields. Secondly, the construction of a numerical model for the seepage process under the effects of thermal conduction coupling. By establishing a geometric model and selecting parameters, setting initial conditions and boundary conditions appropriately, as well as numerically simulating the convective heat transfer coefficients during the dam seepage process, the aim is to provide a more accurate and practical model to predict and assess dam behavior and stability in complex environments. Through these studies, this paper hopes to provide a more scientific theoretical basis and technical support for the design and maintenance of earth-rock dams, enhancing the safety and functionality of the dam body.

2. ANALYSIS OF THE COUPLING MECHANISM BETWEEN SEEPAGE FIELD AND TEMPERATURE FIELD IN EARTH-ROCK DAMS

Figure 1 presents a schematic diagram of the seepage model test box for earth-rock dams. In the research analyzing the coupling mechanism between the seepage field and temperature field, it is necessary to establish reasonable basic assumptions to ensure the applicability and practicality of the model. These assumptions are crucial for accurately simulating physical phenomena in earth-rock dams, such as temperature changes, hydrothermal coupling effects, and their impact on dam stability.

(1) First, considering the actual conditions in earth-rock dams, it is assumed that the dam body is a continuous, homogeneous, isotropic porous medium. This assumption helps simplify the complex three-dimensional problem into a two-dimensional one. Seepage and thermal conduction in the dam are analyzed on this assumed plane, ignoring the temperature gradient in the length direction and assuming that the temperature is essentially uniform along the height of the dam. This simplification helps focus the study on the coupling effects of seepage and temperature in the horizontal direction, making numerical simulation more focused and controllable.

(2) Secondly, in the model, the main modes of seepage and heat transfer are assumed to be thermal convection and thermal conduction. At the same time, considering that large-scale ice-water phase transitions are generally not easy to occur in earth-rock dams, the model does not specifically simulate the phase transition process, but focuses on simulating the hydrothermal coupling phenomena within the operational temperature range of the dam. This assumption helps focus on the direct impact of seepage and temperature changes on dam stability.

(3) Further, for the water flow in the earth-rock dam, a reasonable seepage equation based on Darcy's law is established to describe the water flow in the soil. Here, it is assumed that the internal water flow in the dam is in a laminar state, the flow is stable, and the water and soil skeleton reach thermal equilibrium macroscopically, meaning at any given time point, the temperatures of the water and soil are equal. This assumption simplifies the calculation process, facilitating the handling of the interaction between seepage and temperature in numerical simulations.

(4) Finally, it is assumed that soil physical properties related to temperature, such as unfrozen water content, permeability, specific heat capacity, and thermal conductivity, are functions of temperature. This means that these physical parameters change with temperature changes to simulate the physical behavior more accurately inside the earth-rock dam under different temperatures. By incorporating these temperature-dependent parameters into the model, the dynamic hydrothermal processes under actual conditions can be more realistically reflected, enhancing the predictive and practical value of the model.

For the analysis research on the coupling mechanism between the seepage field and temperature field in earth-rock dams, this paper initially uses COMSOL Multiphysics simulation software to construct the coupled control equations during numerical simulation.

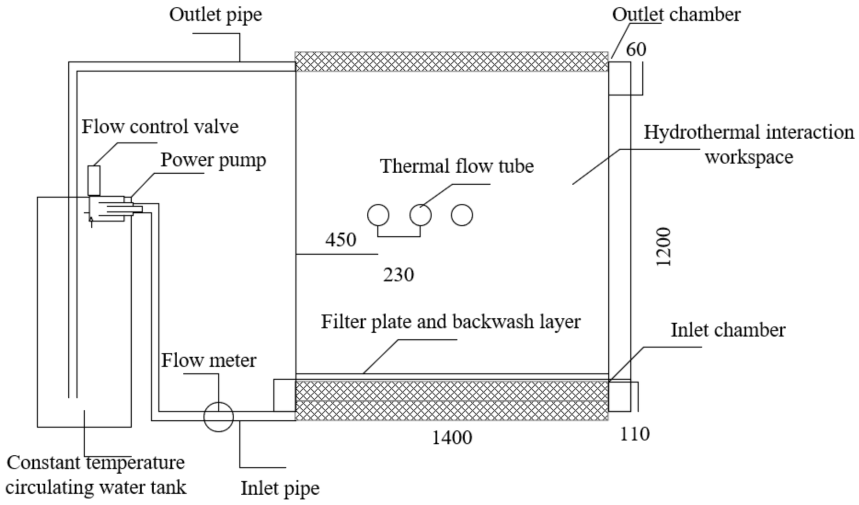


Figure 1. Schematic diagram of the seepage model test box for earth-rock dams

The initial steps in constructing the coupled control equations involve the integrated application of thermodynamics and fluid dynamics. First, it is essential to integrate the hydrothermal coupling processes within the operating temperature range of the earth-rock dams into the heat transfer differential equations, ensuring the energy conservation equation accurately describes the hydrothermal dynamics occurring in the dam environment. Additionally, the model must define the parameters of the heat transfer function for the porous medium, such as porosity, thermal conductivity, and the specific heat and density related to the pore water, to ensure these parameters reflect the actual thermal physical properties of the dam materials. Assuming the equivalent volumetric heat capacity is represented by Z_{rw}, the density of flowing water by ϑ_m, the latent heat generated by the interaction between water flow and heat flow by M, the content of flowing water by ϕ_m, the equivalent thermal conductivity by η_{rw}, the specific heat capacity of movable water by Z_m, the velocity vector by i, the Hamiltonian operator by ∇, and the heat source by W_s, the energy conservation equation considering the hydrothermal coupling process is as follows:

$$Z_{rw}\frac{\partial S}{\partial s}+\vartheta_m M\frac{\partial \varphi_m}{\partial S}+\nabla\left(\vartheta_m Z_m iS-\eta_{rw}\nabla S\right)=W_s \tag{1}$$

Subsequently, the Darcy's law groundwater flow module in COMSOL is used to handle the water flow within the dam. According to Darcy's law, it is assumed that the water flow in the dam is stable laminar flow, which simplifies the usual complex turbulent state. Under this assumption, the fluid is uniformly distributed within the earth-rock dam and exchanges heat with the soil skeleton and the fluid in the pores, achieved by setting appropriate boundary and initial conditions. By coupling the seepage differential equations with the above energy conservation equation, a comprehensive model can be constructed to simulate the interaction between water flow and heat flow in the dam, thereby assessing the thermal stability and structural safety of the dam under different operating conditions. Based on the basic properties of porous media, the parameters in the heat transfer function are defined, and simulation is conducted according to the basic assumptions and built-in modules of the software. Assuming the temperature dependent variable is represented by S, the thickness by f_c, the velocity vector by i, the densities of water and soil by ϑ and ϑ_O respectively, the volumetric fraction of solids in the total by ϕ_O, the Hamiltonian operator by ∇, the effective thermal conductivity by j_{rdd}, and various heat sources by W, W_{nf}, w_0, the coupled equations are as follows:

$$\begin{aligned}
&f_c\left(\vartheta Z_O\right)_{rdd}\frac{\partial S}{\partial s}+f_c\vartheta i\nabla S\\
&+\nabla\xrightarrow[w]{}=f_cW+w_0+f_cW_{nf}\\
&\xrightarrow[q]{}-f_cJ_{rdd}\nabla S\\
&\left(\vartheta Z_O\right)_{rdd}=\varphi_O\vartheta_O+\left(1-\varphi_O\right)\vartheta Z_O\\
&j_{rdd}=\varphi_O j_O+\left(1-\varphi_O\right)J+j_{DI}
\end{aligned}\tag{2}$$

Assuming the density of water by ϑ, the velocity vector by i, the derivation when the Hamiltonian operator by ∇ is used, and various heat sources by W_l, the soil permeability by J, and the dynamic viscosity of water by ω, the seepage differential equation construction is as follows:

$$\begin{aligned}
&\nabla\left(\vartheta\ \ i\right)=W_l\\
&i=-\frac{J}{\omega}\nabla o
\end{aligned}\tag{3}$$

In the study of seepage and thermal conduction coupling effects in earth-rock dams, the simulation of the hydrothermal coupling mechanism mainly focuses on how the interaction between water flow and temperature affects the structure and performance of the dam, especially under conditions without apparent ice-water phase transitions. Using multiphysics simulation software like COMSOL, the dynamic changes in water flow and temperature in the dam can be effectively simulated. This model primarily simulates the flow of percolating water through earth and rock materials and how this flow affects and is affected by the temperature field. In this process, changes in soil physical properties such as porosity and permeability due to temperature variations directly impact the seepage field, which in turn affects the distribution of the temperature field and further heat transfer.

In the numerical simulation of the seepage and thermal conduction coupling effects, it is necessary to simulate the impact of temperature on the permeability and porosity of the earth-rock dam, reflecting the hydrothermal coupling mechanism. This process primarily focuses on how temperature changes affect the interaction between water flow and heat flow in the dam and its long-term impact on dam stability. This simulation is conducted within the normal operating temperature range, without involving ice formation and melting, using COMSOL numerical software for complex multiphysics analysis, setting appropriate physical parameters, such as the temperature dependence of soil and water, and how these parameters change with temperature. Through such analysis, a more accurate understanding of the behavior of earth-rock dams under various climate conditions can be achieved, providing a scientific basis for their design and maintenance. Assuming the densities of the water-heat flow mixture, water flow, and heat flow are represented by ϑ, ϑ_1, ϑ_2 respectively, the volumetric fractions of water flow and heat flow by ϕ_1, ϕ_2, the equivalent volumetric heat capacity of the water-heat flow mixture by Z_o, the latent heat generated by the interaction between water flow and heat flow by $M_{1\to 2}$, the equivalent thermal conductivity of the water-heat flow mixture by β_l, the equivalent permeability of the water-heat flow mixture by J, the formulas for controlling the interaction between water flow and heat flow in the earth-rock dam are as follows:

$$\begin{aligned}
&\vartheta=\varphi_U\vartheta_U+\varphi_2\vartheta_2\\
&Z_o=\frac{1}{\vartheta}\left(\varphi_1\vartheta_1 Z_{O,U}+\varphi_1\vartheta_1 Z_{O,2}\right)+M_{1\to 2}\frac{\partial \beta_l}{\partial S}\\
&\beta_l=\frac{1}{2}\frac{\varphi_2\vartheta_2-\varphi_U\vartheta_U}{2\varphi_U\vartheta_U+\varphi_2\vartheta_2}\\
&M=\varphi_U J_U+\varphi_2 J_2\\
&\varphi_U+\varphi_2=1
\end{aligned}\tag{4}$$

Considering the impact of the interaction between water flow and heat flow on the permeability and porosity of the earth-rock dam, assume the permeability and porosity of the dam are represented by v_o and J_o, respectively. The changes in the volume fractions of water flow and heat flow can be defined as follows:

$$\begin{aligned}
&v_o=v\left(1-\varphi_U\right)+0.01\\
&J_o=J\left(1-\varphi_U\right)+1e^{-6}
\end{aligned}\tag{5}$$

3. CONSTRUCTION OF THE NUMERICAL MODEL FOR SEEPAGE PROCESS IN EARTH-ROCK DAMS UNDER THE EFFECTS OF THERMAL CONDUCTION COUPLING

3.1 Geometric model and parameter selection

The aim of this study is to simulate the seepage process in large-scale earth-rock dam structures. The geometric scale and soil parameters of the model need to be adapted to the actual dam environment. Model tests usually adopt the scale of the prototype strata, for example, the scale of the earth-rock dam model might be set to a comparable ratio to the actual dam, such as 50m×40m, to ensure the applicability and accuracy of the simulation results. In the numerical simulation, considering computational efficiency and accuracy, a two-dimensional planar model is chosen for drawing, and symmetry is used to simplify the model to reduce computational load and shorten computation time. Furthermore, the mesh division of the geometric model mainly uses free triangular meshes and adds boundary layer meshes in key areas such as near the interface between the dam body and the water body to better simulate the coupled effects of seepage and thermal conduction.

3.2 Initial and boundary conditions

To ensure the accuracy and practicality of the numerical simulation, appropriate temperature boundary conditions need to be set first. Assume that the earth-rock dam is a homogeneous, isotropic soil body, with the initial temperature uniformly set at 20°C to facilitate the simulation of the thermal state of the dam under normal conditions. In the model, particular attention is paid to the impact of water flow on the temperature distribution: when water flows upward, its temperature is also set at 20°C, simulating the cooling or heating effects of water flow on the soil during its movement. The lower boundary of the model imposes a temperature load of 20°C to simulate the temperature conditions of the dam in contact with the water body, while the upper boundary is defined as a temperature outflow boundary to simulate thermal exchange between the dam and the external environment. Additionally, the left and right boundaries of the dam are set as thermal insulation conditions to prevent lateral thermal flow losses during the simulation, ensuring energy conservation within the model. Figure 2 displays the layout of the experimental temperature measurement points.

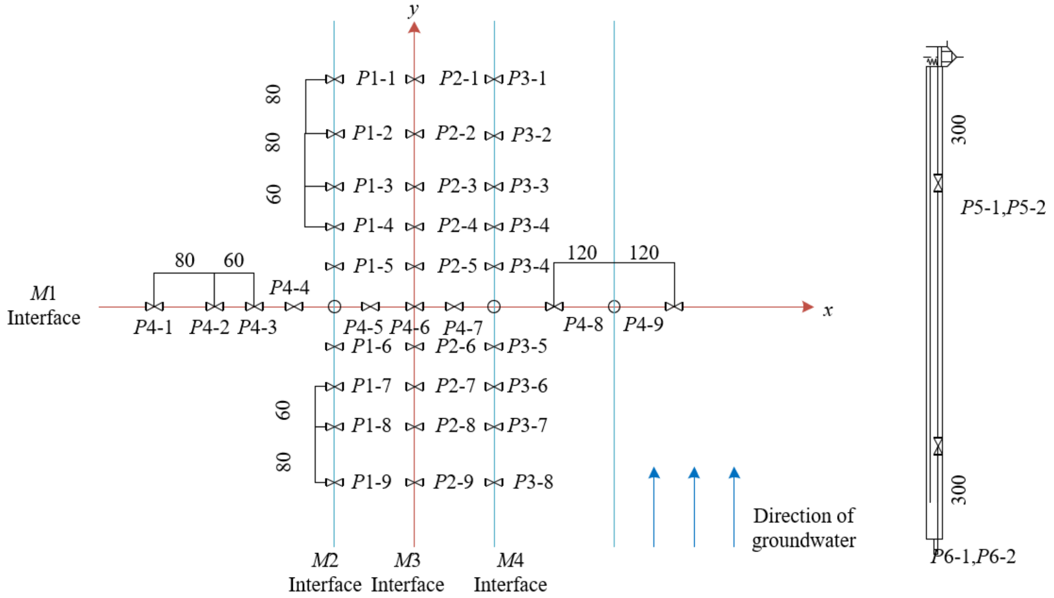


Figure 2. Temperature measurement points layout

The seepage field is defined by applying a hydraulic head to simulate the groundwater flow conditions in the earth-rock dam. According to the actual needs of the simulation and similarity ratio conditions, the lower boundary of the model is set with a specific value of hydraulic head to simulate the natural pressure of the water body on the dam, while the hydraulic head value at the upper boundary is set to 0 to simulate the natural outflow of water. Before conducting the coupled analysis of thermal conduction and seepage, a steady-state study is first carried out to ensure that the seepage field within the model has reached a stable state before freezing or other dynamic operations. This steady-state study only involves Darcy's law to ensure the stability of the seepage field is not affected by other physical processes. The following formula defines the seepage field:

$$G_o = \frac{\Delta M \cdot n_v \cdot v}{J} \tag{6}$$

3.3 Numerical simulation of convective heat transfer coefficients in the seepage process of earth-rock dams

In the seepage process of earth-rock dams under the effects of thermal conduction coupling, studying the characteristics of convective heat transfer is crucial, especially in understanding the complex environment of interactions between water flow and temperature changes within the dam. Unlike studies focused on thermodynamics within rock fractures, research on earth-rock dams pays more attention to the extensive distribution and mutual influence of water flow and temperature fields within the porous media of the dam body. Regarding the study of convective heat transfer characteristics in earth-rock dams, this paper elaborates from the following aspects: Firstly, by using actual operational data and experimental data from earth-rock dams, the existing models of convective heat transfer are validated and adjusted, thereby proposing a more accurate method for calculating convective heat transfer coefficients. Secondly, using the improved model, the impact of factors such as water flow speed, temperature distribution, permeability, and environmental pressure on the convective heat transfer characteristics within the dam is systematically analyzed to enhance the accuracy of predicting temperature and hydraulic behaviors under different operational conditions. Figure 3 shows the conceptual model of convective heat transfer in the seepage process of earth-rock dams.

This paper places multiple thermocouples at various water flow directions within the earth-rock dam to monitor and analyze the evolution of the temperature field in real time and accurately. This setup allows us to derive new formulas for calculating convective heat transfer coefficients based on real-time data, thereby enhancing the accuracy of convective heat transfer coefficient calculations. To simplify the research and reduce the computational load, the model setting proposes several basic assumptions: firstly, considering the effects of thermal conduction and convection, while ignoring the impact of thermal radiation; secondly, assuming that the permeability inside the earth-rock dam is significantly greater than the matrix permeability of the earth and rock materials, thus mainly considering the heat transfer in major permeable pathways such as fractures and pores, ignoring the permeability and heat dissipation within the matrix. Based on these basic assumptions, assuming the total heat flow of the convective heat transfer process is represented by W, the convective heat transfer coefficient by g, the heat transfer area by X, the temperature difference for convective heat transfer by ΔS, the specific heat capacity of water by z_q, the density of water by ϑ_q, and the volumetric flow rate of water by w, according to Newton's law of cooling, we have:

$$W = gX\Delta S = z_q \vartheta_q w_q \Delta S \tag{7}$$

Assuming the temperature distribution on the permeable pore surface of the earth-rock dam by $S_u(a)$, and the temperature distribution of the flowing water by $S_q(a)$, and the length and radius of the earth and rock samples of the dam by M and E, according to Newton's law of cooling differential formula, we can get:

$$\begin{aligned} dW &= G\left(S_u(a) - S_q(a)\right)dX \\ &= g\left(S_u(a) - S_q(a)\right)Mda \end{aligned} \tag{8}$$

$$W = 4MgE\int_0^E \left(S_u(a) - S_q(a)\right)da \tag{9}$$

To calculate the heat transfer equations under steady state, it is first necessary to determine the values of S_u and S_q. Assuming the temperature at the center point of the permeable pore surface of the earth-rock dam is represented by S_{u0}, and the outer wall temperature of the earth and rock samples of the dam by S_z, the calculation formula is:

$$S_u = S_{u0} + \left(S_z - S_{u0}\right)\frac{a}{E}, a \in [0, E] \tag{10}$$

Combining Eqs. (8) and (9), we have:

$$W = 4MgE\left[\frac{1}{2}\left(S_{u0} + S_z\right) + S_q(a)\right] \tag{11}$$

In the convective heat transfer model of the seepage process constructed for the earth-rock dam, the water flows in two dimensions within the permeable pores of the dam, $S_q(a)$ can be approximated by the average water temperature at the inlet and outlet, which can be obtained experimentally, that is, the average water temperature along the longitudinal axis of the permeable pores of the dam, the calculation formula is:

$$S_q(a) = \frac{1}{2}\left(S_{q1} + S_{q2}\right) \tag{12}$$

Since the center point of the permeable pores in the dam is far from the boundaries of the earth and rock samples of the dam, the temperature at the center point is minimally influenced by external environmental factors. Thus, S_{u0} can be equated to the average temperature of the fracture surfaces on both sides of the center point of the distributed permeable pores of the dam, the calculation formula is:

$$S_{u0} = \frac{1}{2}\left(S_{u1} - S_{u2}\right) \tag{13}$$

Based on the above processes, the following formula for calculating the convective heat transfer coefficient g can be obtained:

$$g = \frac{z_q \vartheta_q w_q \left(S_{q2} + S_{q1}\right)}{2ME\left[\frac{1}{2}\left(S_{u1} - S_{u2}\right) + S_z - \left(S_{q1} + S_{q2}\right)\right]} \tag{14}$$

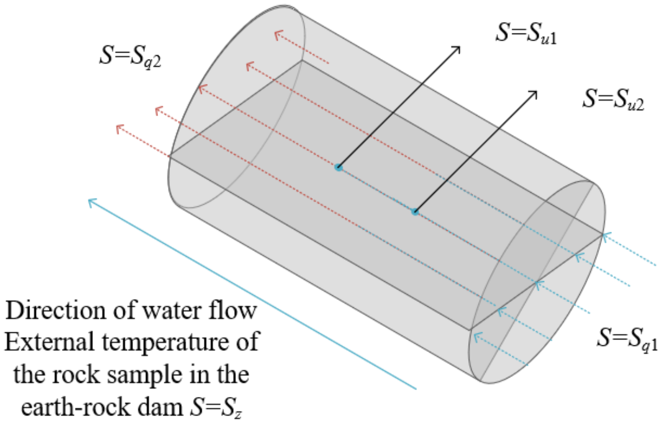
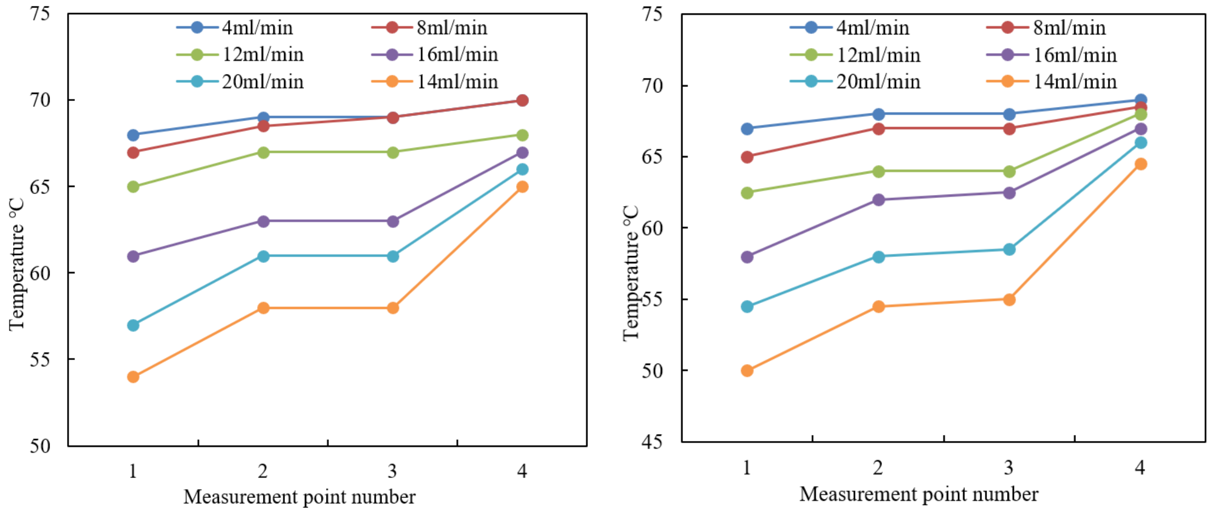


Figure 3. Conceptual model of convective heat transfer in the seepage process of earth-rock dams

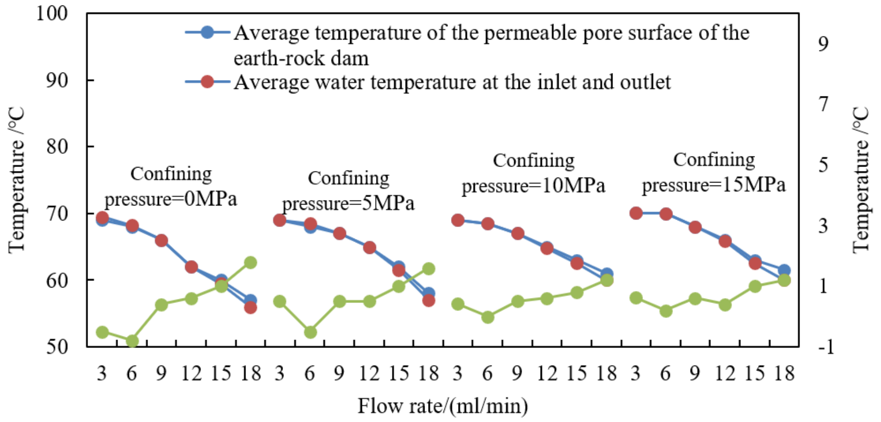
4. RESULTS AND ANALYSIS

From Figure 4, under confining pressures of 0MPa and 15MPa, temperature observation data during the convective heat transfer process in the permeable pores of the earth-rock dam show that as the flow rate increases (from 4ml/min to 20ml/min), temperatures at various measurement points generally exhibit a declining trend. For example, under a 0MPa confining pressure, the temperature at measurement point 1 decreases from 68°C to 57°C, and at measurement point 4 from 70°C to 66°C. The same trend is observed under a 15MPa confining pressure, although overall temperature levels are slightly higher, with measurement point 1 dropping from 67°C to 54.5°C, and measurement point 4 from 69°C to 64.5°C. Additionally, under a 15MPa confining pressure, the drop in temperature is more significant than at 0MPa, suggesting that increasing confining pressure enhances the material's thermal conductivity or alters permeability, thus affecting heat transfer efficiency. These experimental data demonstrate that as the flow rate increases, internal temperatures within the earth-rock dam generally decrease, indicating that convective heat transfer effects are more pronounced at higher flow rates. Additionally, increased confining pressure promotes heat transfer, resulting in higher temperature drops at the same flow rates. These observations support the validity of the numerical model and hydrothermal coupling mechanism proposed in this study, indicating that the model can accurately reflect the thermal behavior and seepage characteristics of real earth-rock dams under different operational conditions.

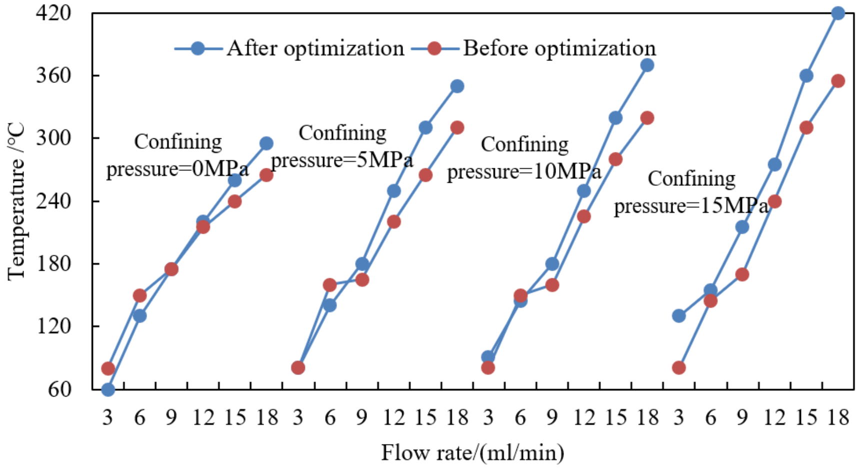


(1) 0*MPa* (2) 15*MPa*

Figure 4. Temperature changes at various measurement points in the convective heat transfer process of earth-rock dam permeable pores under 0MPa and 15MPa confining pressure



(1) The relationship between temperature changes and water flow rate



(2) Analytical solution for convective heat transfer as a function of water flow rate

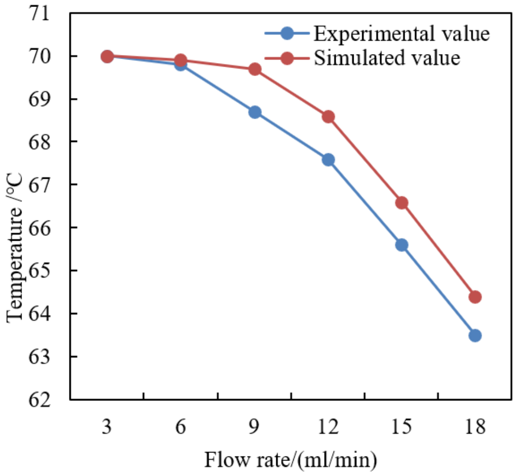
Figure 5. Relationship between temperature and convective heat transfer coefficients with water flow rate at an initial temperature of 70 degrees in earth-rock dam samples

Data from Figure 5 shows that under different confining pressures from 0MPa to 15MPa, as the water flow rate increases, the average temperature on the permeable pore surface of the earth-rock dam gradually decreases, and the average water temperature at the inlet and outlet exhibits a similar trend. For example, at 0MPa, when the water flow rate increases from 3ml/min to 18ml/min, the average temperature of the dam drops from 69°C to 57°C. Under the highest confining pressure of 15MPa, the corresponding temperature drops from 70℃ to 61.5℃. Moreover, the convective heat transfer coefficients increase with increasing flow rate, from 60 W/m²K to 295 W/m²K at 0MPa, and from 130 W/m²K to 420 W/m²K at 15MPa. This indicates that with increasing confining pressure, convective heat transfer coefficients significantly improve. The optimized formulas show higher heat transfer coefficients under all confining pressures compared to before optimization. These results validate the effectiveness of the coupling mechanism between seepage and temperature fields in earth-rock dams, especially that the optimized formulas for convective heat transfer coefficients can more accurately reflect the heat transfer characteristics under different water flow conditions. The increased convective heat transfer coefficients are closely related to increases in water flow rate and confining pressure, highlighting the significant role of convective effects in the thermal management of earth-rock dams. The optimized formulas provide higher heat transfer coefficients, which are crucial for more accurately predicting and assessing the thermal behavior and structural safety of earth-rock dams under complex environmental conditions.

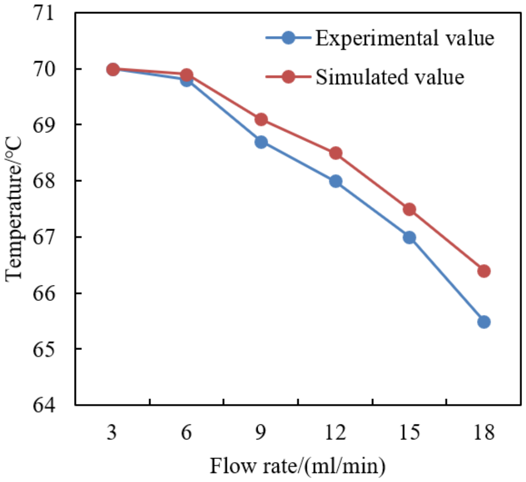
Table 1. Simulation results of outlet water temperatures at an initial temperature of 70 degrees in earth-rock dam samples

Confining Pressure/*MPa*	Flow Rate (*ml/min*)	Outlet Water Temperature/℃
0	3	69.25
	6	69.25
	9	69.25
	12	68.12
	15	66.52
	18	64.21
5	3	69.58
	6	69.54
	9	69.54
	12	68.21
	15	67.59
	18	65.26
10	3	69.58
	6	68.95
	9	69.32
	12	68.45
	15	67.52
	18	67.51
15	3	69.32
	6	69.25
	9	69.87
	12	67.58
	15	68.21
	18	68.23

The data in Table 1 displays the simulation results of outlet water temperatures under different confining pressures (0MPa, 5MPa, 10MPa, 15MPa) and flow rates (3ml/min to 18ml/min). Overall, as the flow rate increases, the outlet water temperatures at each confining pressure level show a decreasing trend. For example, under a 0MPa confining pressure, the outlet water temperature decreases from 69.25℃ at 3ml/min to 64.21℃ at 18ml/min. Similarly, under a 15MPa confining pressure, the outlet water temperature drops from 69.32℃ at 3ml/min to 68.23℃ at 18ml/min. This trend indicates that with increasing flow rates, heat exchange within the dam becomes more intense, leading to a reduction in outlet water temperatures. This study, through numerical simulation of the coupling mechanism between the seepage field and temperature field of the earth-rock dam, demonstrates the model's effectiveness and accuracy in predicting the dam's thermal behavior under different operational conditions. The trend in outlet water temperatures aligns with theoretical expectations, showing that as flow rate increases, convective heat transfer is enhanced, thereby affecting the reduction in water temperature. Additionally, the increase in confining pressure also influences water temperature changes, related to the permeability and heat transfer characteristics of dam materials under different confining pressures.



(1) 0*MPa*



(2) 15*MPa*

Figure 6. Comparison of simulated and experimental outlet water temperatures under 0mpa and 15mpa confining pressure at an initial temperature of 70 degrees in earth-rock dam samples

Figure 6 compares the experimental and simulated outlet water temperatures under 0MPa and 15MPa confining pressures. The data shows that the simulated values are very close to the experimental values, indicating high accuracy of the model. Under a 0MPa confining pressure, as the water flow rate increases from 3ml/min to 18ml/min, the experimental values drop from 70℃ to 63.5℃, while the simulated values decrease from 70℃ to 64.4℃. Under a 15MPa confining pressure, the experimental values drop from 70℃ to 65.5℃, and the simulated values from 70℃ to 66.4℃. These results demonstrate that although both exhibit a gradual decrease in temperature with increasing flow rates, simulated values are generally slightly higher than experimental values, which is related to certain assumptions and boundary conditions set in the model. These comparative data emphasize the effectiveness of the numerical model for the coupling of seepage and temperature fields in earth-rock dams proposed in this paper. The high consistency between simulated and experimental values proves the model's accuracy in predicting temperature changes under different confining pressures and flow rates. Additionally, the model captures the trend of decreasing temperatures with increasing water flow rates, further validating the applicability of the hydrothermal coupling control equations for earth-rock dams. Thus, this numerical model not only provides important tools for understanding and predicting the behavior of earth-rock dams under actual operating conditions but also offers theoretical bases and technical support for dam design and safety assessment.

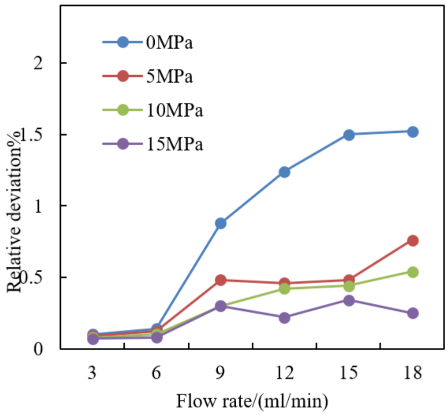


Figure 7. Analysis of relative deviations between simulated and experimental outlet water temperatures at different confining pressures (0, 5, 10, 15MPa)

Figure 7 displays the relative deviations between simulated and experimental outlet water temperatures under different confining pressures (0MPa, 5MPa, 10MPa, 15MPa) and varying water flow rates (3ml/min to 18ml/min). Under a 0MPa condition, the relative deviations increase gradually from 0.1% to 1.52% as the flow rate increases. For 5MPa and 10MPa confining pressures, the relative deviations grow to varying extents with increasing flow rates, but at 15MPa, the deviations are relatively smaller, peaking at no more than 0.34%, indicating improved accuracy of model predictions under higher confining pressures. These relative deviation data suggest that the precision of model predictions improves with increasing confining pressures, particularly at higher pressures (15MPa). The overall low deviations indicate the model's applicability and effectiveness in actual dam operating environments. These results verify the accuracy of the numerical model in simulating complex coupled behavior of seepage and temperature fields, especially under high confining pressures, where the model can also more accurately predict changes in water temperature.

5. CONCLUSION

This paper has thoroughly analyzed the coupling mechanism between the seepage and temperature fields in earth-rock dams, successfully establishing a hydrothermal coupling mechanism that includes coupled control equations for the seepage and temperature fields, and has constructed a numerical model for the seepage process under the effects of thermal conduction coupling. The study primarily utilized a combination of experimental and simulation methods to investigate the temperature changes and convective heat transfer characteristics of earth-rock dams under various confining pressures and water flow rates. This included analyzing changes in the temperature of the dam’s permeable pore surfaces, comparing simulated and experimental water temperatures at the inlet and outlet, and analyzing relative deviations. The results demonstrate that the model can effectively simulate temperature changes under different confining pressures and flow rates, and accurately predict changes in convective heat transfer coefficients, particularly showing higher predictive accuracy under high confining pressure conditions. These findings confirm that the behavior and stability of earth-rock dams in actual operational environments can be effectively predicted and assessed through the proposed numerical model and hydrothermal coupling mechanism.

The primary value of this research lies in providing a method for accurately simulating the behavior of earth-rock dams under complex environmental conditions, which is significant for design, maintenance, and risk management. Additionally, the coupling analysis of temperature and permeability characteristics provides theoretical support and practical guidance for the long-term stability and safe operation of earth-rock dams. However, the study also has certain limitations, such as the impact of boundary condition settings and the selection of physical parameters on the model’s predictive accuracy. Future research needs to further refine the selection and adjustment of these parameters. Moreover, the universality of the model and its adaptability to abnormal environmental factors, such as extreme climate changes, still need further verification.

Future research should focus on optimizing model parameters to improve the model’s applicability and accuracy across different earth-rock dam materials and a broader range of environmental conditions. Additionally, research should extend to addressing new issues encountered in the actual operation of earth-rock dams, such as dealing with extreme meteorological conditions brought about by climate change, and integrating real-time monitoring data for real-time or predictive analysis to enhance the functionality of dam safety monitoring and early warning systems. Further studies on the nonlinear dynamic behaviors in the hydrothermal coupling process will also be an important part of future work.

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