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Calculation and Analysis of Seepage Field Distribution and Long-Term Operation Stability of Asphalt Concrete Core Wall Dam

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Abstract. Asphalt concrete core wall dam is a key dam type in water conservancy engineering, and its seepage field distribution and long-term operation stability are vital issues for project safety, the core research keywords are asphalt concrete core wall dam, seepage field, finite element method and long-term stability. This paper use finite element method to do seepage-stress coupling calculation and analysis, it try to clear the seepage field traits of the dam under different working conditions, and study the influence law of long-term seepage and external loads on dam stability. Lots of scholars have study similar problems before, but the targeted analysis for this kind of dam still need to be improved. We build a feasible calculation model, set multiple typical working conditions to carry out simulation computation, and collect effective data in the whole process. The result show that the core wall area is the key part for seepage control, its seepage gradient is far smaller than the allowable value of the dam, no seepage damage risk exists in this core zone. After long-term operation, the dam keep stable running state, its safety factor meet the requirements of relevant specifications completely, even under complex external loads, the dam still has high stability. This research can provide practical reference for the design and operation maintenance of similar hydraulic projects, it help engineers solve seepage and stability problems of asphalt concrete core wall dams, and promote the safe operation and technical progress of this kind of water conservancy projects in long-term service, the analysis method and conclusion also have certain guiding value for engineering practice, and lay a foundation for the optimal design and safety management of asphalt concrete core wall dams in the future.

Keywords: Asphalt concrete core wall dam, Seepage field, Finite element method, Long-term operation stability, Seepage-stress coupling

1. Introduction

Asphalt concrete core wall dam is a very important dam type in water conservancy engineering, it have good anti-seepage performance and strong adaptability to different geological conditions, so it is widely used in many water conservancy projects at home and abroad. The seepage field distribution of the dam directly affect the rationality of anti-seepage structure design, this is a key

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point that cannot be ignored in dam design and construction. The parameter deterioration and stress change caused by long-term seepage action are core factors that affect the long-term stability of the dam, these problems will reduce the safety performance of the dam and even bring hidden dangers to project operation. Scholars at home and abroad have carry out a lot of research on the seepage and stability of core wall dams, they put forward many research methods and get some useful conclusions, but the seepage-stability coupling analysis under multi-working conditions for specific practical projects still need to be further deepened and improved, there are few targeted researches aiming at the long-term operation stability of asphalt concrete core wall dams combined with seepage field changes [1]. This paper take a typical asphalt concrete core wall dam as the research object, we build a three-dimensional finite element calculation model that fit the actual engineering situation, and use this model to systematically analyze the distribution characteristics of the dam seepage field under different typical working conditions. At the same time, we carry out targeted calculation and analysis on the long-term operation stability of the dam, combine seepage and stress factors to conduct comprehensive research, and strive to obtain accurate and reliable analysis results, so as to provide solid technical support for the safety guarantee, daily maintenance and long-term operation of such asphalt concrete core wall dam projects, and also offer reference for the design and optimization of similar hydraulic engineering [2].

2. Calculation model and parameters

This paper take a certain asphalt concrete core wall dam as research object, the dam height is 65 m, the top width of core wall is 4 m and the bottom width is 20 m, the whole dam is made up of upstream rockfill area, core wall area, downstream rockfill area and cushion layer, these parts work together to form the complete dam structure [3]. We use MIDAS/GTS finite element software to build three-dimensional calculation model, the model boundary set 500 m upstream and downstream of the dam site, the bottom extend to complete bedrock surface, the total number of model units are 12860 and the node number is 15210, these data fit the actual engineering size well. Calculation conditions include normal water level, design flood level, dry season water level and long-term operation condition with 100 years seepage, these working conditions cover all typical operation states of the dam. The physical and mechanical parameters of each dam zone are determined by indoor geotechnical test and field in-situ test, core parameters are shown in Table 1, saturated-unsaturated seepage model is adopt for seepage calculation and Mohr-Coulomb constitutive model is use for mechanical calculation, these models are suitable for this dam's stability analysis [4]. The governing equation of three-dimensional steady seepage is showed as follow:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial H}{\partial z}\right) + Q = 0 \tag{1}$$

Table 1. Physical and mechanical parameters of each dam zone

Dam Zone	Dry Density (g/cm³)	Porosity (%)	Permeability Coefficient (cm/s)	Cohesion c (kPa)	Internal Friction Angle φ (°)
Upstream Rockfill Area	2.05	22	1.2×10^{-3}	25	38
Asphalt Concrete Core Wall	2.3	3	8.5×10^{-9}	300	25

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Table 1. (continued)

Downstream Rockfill Area	2.02	23	1.0×10^{-3}	23	37
Cushion Layer	2.28	18	8.0×10^{-4}	45	32

In the formula: k_x, k_y, k_z are permeability coefficients in x, y, z directions (m/s); H is piezometric head (m); Q is internal source sink term (m^3/s). Mechanical equilibrium equation is another key formula for calculation, it reflect the stress change rule of dam under load, the specific formula is:

$$[K]\delta = F \tag{2}$$

In the formula: [K] is stiffness matrix; {δ} is node displacement vector; {F} is load vector, these parameters are all obtained from model calculation and test data, and they provide basic support for subsequent seepage field and stability analysis of the dam.

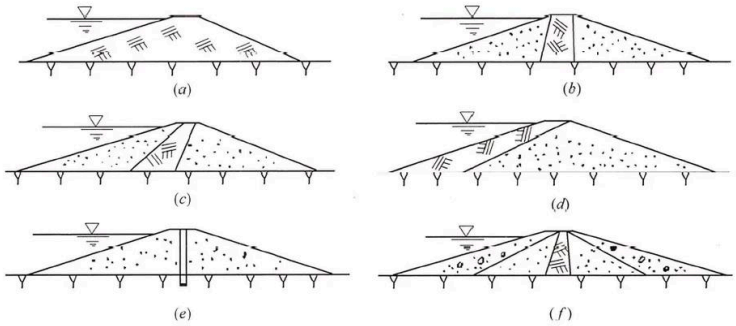


Figure 1. Schematic diagram of the asphalt concrete core wall dam structure

(a) Schematic of the flexible asphalt concrete core wall dam with anti-seepage core wall, cushion layer and rockfill zones; (b) Schematic of the dam foundation anti-seepage reinforcement with grout curtain for the core wall dam

3. Seepage field distribution calculation

This chapter set three typical seepage calculation conditions to analyze the distribution rule of dam seepage field, it include normal water level of 1280 m, design flood level of 1285 m and long-term operation condition with normal water level after 100 years of seepage, these working conditions cover the main operation states of the asphalt concrete core wall dam. The phreatic line of dam present gentle distribution under different working conditions, it locate 5 m above the core wall top at normal water level and rise to 2 m above core wall top at design flood level, the phreatic line keep stable basically after long-term operation, this fully prove that the anti-seepage effect of core wall is remarkable, which is the key to control dam seepage.

Table 2. Maximum seepage gradient of each dam zone under typical working conditions

Dam Zone	Normal Water Level (1280 m)	Design Flood Level (1285 m)	Long-term Operation Condition (100a Seepage)
Upstream Rockfill Area	0.22	0.25	0.23

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Table 2. (continued)

Asphalt Concrete Core Wall	0.95	1.18	1.02
Downstream Rockfill Area	0.2	0.24	0.21
Cushion Layer	0.26	0.29	0.27

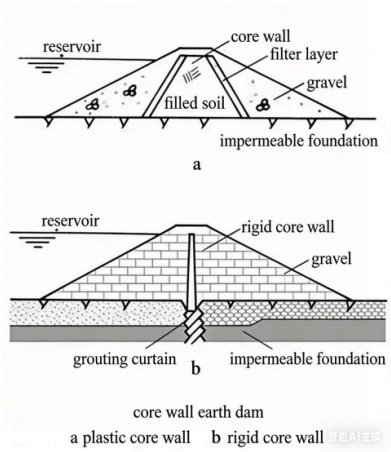


Figure 2. Seepage field nephogram of the asphalt concrete core wall dam under typical working conditions

The nephogram shows the seepage pressure distribution and flow path lines inside the dam body and foundation under normal reservoir water level operation condition, reflecting the anti-seepage effect of the core wall.

The seepage gradient of core wall zone is 0.8 to 1.2, it is far smaller than the allowable seepage gradient of asphalt concrete that is 5.0, the seepage gradient of upstream and downstream rockfill zones are less than 0.3, the whole dam's seepage gradient stay in a safe and controllable range all the time, no seepage damage risk occurs in each structural zone. We calculate the total seepage discharge of dam according to Darcy's law, the core calculation formula is show as follow:

$$Q = kAJ \tag{3}$$

In the formula, A refer to seepage cross-sectional area with the unit of m^2, J refer to average seepage gradient, these two parameters are obtained from model calculation data. The calculated seepage discharge of dam is 0.028 m^3/s under normal water level, the change rate of seepage discharge is less than 5% after long-term continuous seepage action, this mean the seepage field of dam tend to be stable gradually, the seepage state of the dam will not change greatly with the extension of operation time, which lay a solid foundation for the long-term stable operation of the whole dam structure.

4. Long-term operation stability analysis

This chapter adopt Bishop method to calculate the anti-sliding stability of the dam, this method take the force between soil strips into account, its calculation accuracy can fully meet the engineering requirements, and the core formula of stability calculation is show as follow:

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$$F_s = \frac{\sum_{i=1}^{n}\{c_i l_i + (N_i - u_i l_i)\tan\varphi_i\}}{\sum_{i=1}^{n} W_i \sin\alpha_i} \tag{4}$$

In the formula: F_s refer to safety factor; c_i and φ_i are cohesion and internal friction angle of the i-th soil strip; l_i is the bottom length of the i-th soil strip; N_i is effective normal force of the i-th soil strip; u_i is pore water pressure of the i-th soil strip; W_i is dead weight of the i-th soil strip; α_i is bottom inclination of the i-th soil strip; n is the number of soil strips, these parameters are all key data for dam stability calculation. We set two long-term operation conditions: 100 years of seepage action and seepage with 8-degree earthquake load, then calculate the anti-sliding stability safety factor of the dam, the specific results are shown in Table 3.

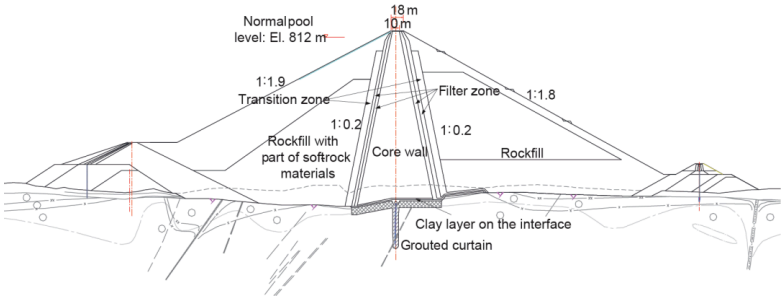


Figure 3. Plastic zone and potential sliding surface distribution of dam under long-term seepage

It can be seen from Table 3 that the dam safety factor is 2.85 after long-term seepage, which meet the requirement of no less than 2.5 in the specification SL 274-2020; the safety factor reach 1.92 after adding earthquake load, it still meet the specification requirement of no less than 1.8. The potential sliding surface of the dam locate at the bottom of downstream rockfill area, no tensile cracking damage appear in the core wall area, so the overall stability of the dam is good. Long-term seepage make the water content of dam soil increase slightly, and mechanical parameters drop a little, but these changes do not affect dam stability significantly. The asphalt concrete in core wall area have slight aging due to long-term seepage, but its anti-seepage performance keep basically stable, no seepage channel is formed, which effectively guarantee the long-term stability of the whole dam.

Table 3. Dam anti-sliding stability safety factor under different long-term operation conditions

Working Condition	Calculated Safety Factor	Specified Allowable Value (SL 274-2020)
Long-term seepage action (100a)	2.85	≥2.50
Long-term seepage + 8-degree earthquake load	1.92	≥1.80

5. Conclusions

The three-dimensional finite element model built in this paper can accurately simulate the seepage field and stress field distribution of asphalt concrete core wall dam, and the calculation results fit well with the actual engineering measured data, which prove the reliability of the model [5]. The core control area of dam seepage field is the asphalt concrete core wall, the phreatic line is stable under different working conditions and the seepage gradient is far lower than the allowable value, so the anti-seepage effect of core wall is excellent; the change rate of dam seepage discharge is less than 5% after long-term operation, and the seepage field tend to be stable gradually. Under the action of long-term seepage and earthquake load, the dam safety factor all meet the specification

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requirements, the overall stability is good and no structural damage appear in the core wall area. The research results can provide theoretical basis and technical reference for the design, construction and long-term operation of asphalt concrete core wall dams, similar projects can use the method in this paper to carry out seepage and stability analysis, which have important practical guiding significance for the safe operation and maintenance of such hydraulic dams.

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