Numerical study on percolation and dam slope's stability of impermeable wall composed by clay and concrete for earth-rock dam

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Abstract. In order to study the percolation and dam slope's stability of an impermeable wall composed by clay and concrete for earth-rock dam, the steady seepage field of a reservoir in Jiangxi is numerically simulated by using finite element method based on the basic principles of saturated and unsaturated seepage under different ratios of clay to concrete. The results of the flow field of steady seepage are carried out and the dam slope's stability is analyzed. We found relatively minor impacts of concrete proportion on the discharge of seepage per unit width and the dam slope's stability. In this study, the impermeability performance of the impermeable wall is concerned. The results showed that impermeable effect of the impermeable wall has not obviously changed if the concrete proportion is below 0.43. When the proportion of concrete exceeds 0.43, the anti-seepage effect of the impermeable wall begins to change significantly. Besides, when the proportion of concrete reaches 1.0, the reduction of water level at front and behind impermeable wall, the discharge of seepage per unit width, and the safety factor of the Bishop method are all infinitely close to the value of the best anti-seepage performance and the most stable state of the dam slope.

Key words: Impermeable wall, Finite element analysis, Percolation, Dam slope's stability

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1. Introduction

Several types of earth-rock structures have been applied in water resources management [1-5]. As one type of dam structure, earth-rock dams are widely used since the few decades due to their advantages such as low investment, simple construction, fully use local materials and low requirements for topographic and geological conditions. Regarding all types of reservoirs in China which reaching up to 99%, 30% of dam collapse accidents due to seepage and slope instability of earth-rock dams [6].

Impermeable wall is the key component of the whole earth-rock dam seepage-proof system, and its quality is directly related to the safety of the whole project. There are several studies on seepage and slope stability of earth-rock dam with concrete impermeable wall that have been done by local researches in China. Xin [7] studied the depth optimization of cut-off wall and its anti-seepage effect. Ni [8] and Wang et al. [9] studied the influence of water level rise and fall of reservoir on seepage of earth-rock dam and stability of dam slope. Gao et al. [10] studied seepage characteristics of imperfect cut-off wall in earth-rock dam reinforcement project. However, there is little research on seepage and slope stability of earth-rock dam with clay-bonded concrete cut-off wall. Therefore, this paper simulates the steady seepage field of earth-rock dam with clay-concrete cut-off wall by using finite element method based on the basic theory of saturated-unsaturated unstable seepage of porous media. To analyze the stability of dam slope under the condition of changed reservoir water level, the seepage parameters are compared for different clay-concrete ratio conditions and Bishop method is applied in this study. This study has beneficial to provide reference basis for seepage of earth-rock dam with clay-bonded concrete cut-off wall, stability of dam slope and designation of safe operation system of reservoir.

2. Material and Methods

2.1 Governing equation of unsaturated seepage flow

Frelund and Rahardjo [11] believe that the seepage in unsaturated soil conforms to Darcy's law and continuity equation. However, the permeability coefficient in unsaturated soil is no longer a constant, but a function of matrix suction, and the volume moisture content of soil changes with time. The seepage governing equations of unsaturated soil can be obtained by introducing Darcy's law into the seepage continuity equation as follows [12-13]:

\[
\frac{k_x}{\gamma_w} \frac{\partial^2 U_x}{\partial x^2} + \frac{k_y}{\gamma_w} \frac{\partial^2 U_y}{\partial y^2} + \frac{\partial \theta_w}{\partial t} = 0
\]  

(1)

In the formula (1): \( k_x, k_y \) are permeability coefficients in x and y direction respectively; \( \gamma_w \) is the volume weight of water; \( \theta_w \) is the volumetric water content; \( t \) is the time.

2.2 Stability analysis equation of Bishop Method

The rigid body limit equilibrium method is used for the static stability calculation of dam slope. For the stable seepage period or the reservoir water level falling period, when the simplified Bishop method is used for the stability analysis, the formula of the effective stress method anti-sliding stability safety factor is:

\[
K = \left[ \frac{c' \cdot b \cdot \sec \beta + (w_1 + w_2) \sec \beta - (U - \gamma_w \cdot z) b \cdot \sec \beta \cdot \tan \phi'}{\sum (w_1 + w_2) \sin \beta} \right] / (1 + \tan \phi' \tan \beta / k)
\]  

(2)
For the reservoir water level falling period, when the simplified Bishop method is used for stability analysis, the formula for safety factor of anti-sliding stability of total stress method is as follows,

\[
K = \frac{\sum (c' \cdot b \cdot \sec \beta + (W \sec \beta - U_1 \cdot b \cdot \sec \beta) \tan \varphi_{cu})}{W \sin \beta} \left(1 + \tan \varphi_{cu} \tan \beta / k\right)
\]

(3)

In the formulas (2) and (3): \(c', \Phi'\) are the effective strength indexes; \(c_{cu}, \varphi_{cu}\) are the consolidated undrained total strength indexes; \(b\) is the width of soil strip; \(w\) is the solid weight of soil strip; \(w_1\) is the solid weight of strip above water level outside dam slope; \(w_{1}'\) is the sum of floating weight and solid weight of bars below the phreatic line above the water level outside the dam slope; \(w_2\) is the distance between the water level outside the dam slope and the midpoint of the strip bottom; \(Z\) is the distance between the water level outside the dam slope and the midpoint of the strip bottom; \(u_i\) is the pore water pressure in the dam before the water level of the reservoir drops; \(u\) is the pore water pressure in the dam during the period of stable seepage or reservoir water level falling; \(\beta\) is the angle between the gravity line of the block and the radius passing through the midpoint of the bottom surface of the block; \(\gamma_w\) is the volume weight of water.

2.3 Determination of pore water pressure
The calculation of the pore water pressure of the dam body and dam foundation during the stable seepage period when the reservoir level is the design flood level and the check flood level can be determined according to the flow network calculated by seepage analysis, that is, the pore water pressure at any point on the same equipotential line in the flow network diagram is equal to the vertical head pressure from that point to the intersection of the equipotential line and the saturation line. When the effective stress method is used to calculate the upstream slope stability under the water level drops suddenly and the dissipation of pore water pressure is considered, the result of unsteady seepage period is used to calculate and the determination method of pore water pressure is the same as that of stable seepage period.

3. Results and Discussions
3.1 Reservoir overview
A reservoir in Jiangxi Province is a medium-sized reservoir, which is mainly used for irrigation, flood control, aquaculture and other comprehensive utilization and supplement of industrial and domestic water in the county. In the dam anti-seepage treatment scheme, the clay core wall is backfilled with the grab sleeve well and the anti-seepage wall is built with high-pressure jet grouting. The clay core wall is punched at the upper part and the effective thickness of the core wall is not less than 0.65 m. The anti-seepage wall is built with high-pressure jet grouting at the lower part. The thickness of the anti-seepage wall is \(\delta \geq 0.20\) m, and the bottom of the anti-seepage wall extends into the bedrock 0.50 m. The upstream normal water level is 58.90 m, the design flood level is 60.50 m, the check flood level is 62.40 m, and the dead water level is 48.40 m. The cross section of a dam in Jiangxi is shown in Figure 1.
Before the construction of clay core wall, the dry bulk density test with different times of ramming is carried out. The number of ramming is determined to be 14-16, the moisture content of soil material is all controlled at 22.7-28.7, and the dry bulk density detection is up to 1.47-1.55 g/cm$^3$. High pressure jet grouting seepage control wall, the slurry density control is 1.6 g/cm$^3$, the pressure of high pressure water is 35 MPa, and the cement slurry pressure is 0.5 MPa.

3.2 Model design and Establishment

The cutoff wall of a reservoir dam in Jiangxi Province is a combination of clay and concrete. The upper part of the cutoff wall is clay core wall which is 8.9 m, and the lower part is concrete cutoff wall which is 12.1 m, and the total length is 21 m. In order to discuss and analyze the influence of impervious wall formed by the ratio of clay to concrete on the seepage and the stability of dam slope, eight working conditions of concrete accounting for the whole impervious wall height (hereinafter referred to as "the ratio of concrete") are selected for modeling, which are 0, 0.14, 0.29, 0.43, 0.58, 0.71, 0.83 and 1.0 respectively.

A two-dimensional seepage finite element model of a reservoir dam in Jiangxi Province is established according to the cross section of the dam (as shown in Figure 2). The seepage field under the condition of the change of reservoir water level is the result of the interaction of saturated seepage and unsaturated seepage. The selection of soil-water characteristic curve and permeability coefficient curve characterizing the unsaturated seepage characteristic is complex. At present, the soil-water characteristic curve and permeability coefficient curve are difficult to be obtained directly by theoretical analysis method, so they are estimated through corresponding mathematics model based on a small number of test values. SEEP/W module of Geo-Studio software can estimate the soil water characteristic curve of core wall and dam shell respectively by saturated volume water content (void ratio) of material, clay spline function and rockfill spline function provided by the module. At the same time, the module can estimate the permeability coefficient curve of the material through the saturated permeability coefficient of the corresponding material, the soil water characteristic curve and the Fredlund-Xing model provided by the module itself. Then, the seepage calculation results under various working conditions are transferred into slope/W module, and the Mohr-Coulomb criterion modified by Fredlund and Bishop method in limit equilibrium method are used to analyze the stability of upstream dam slope[7-8].

![Figure 1. The cross section of a dam in Jiangxi.](figure1.png)
Taking the concrete ratio of 0.58 as an example, the seepage simulation results are shown in Figure 3. It can be seen from the simulation results that the maximum seepage gradient of the dam occurs in the impervious wall, and the gradient values are all within the allowable gradient range. The local seepage stability of the dam body is good, and the possibility of seepage failure is small. During the stable seepage period under various working conditions, the phreatic line escapes at the position close to the slope. The phreatic line is mainly lowered in the anti-seepage wall, and falls slowly in the dam body behind the anti-seepage wall. The anti-seepage performance of the dam is good. The distribution of the seepage calculation equipotential line of the dam conforms to the seepage law of the general concrete core wall.

Taking the concrete ratio of 0.58 as an example, the dam slope stability simulation results are shown in Figure 4. Under the normal water level, design flood level and design flood level, the calculated safety factors $K$ of Bishop method at the downstream of dam slope are 1.568, 1.552 and 1.532 respectively. The design code for roller compacted earth rock dam (SL274-2001) requires that the minimum safety factor of anti-sliding stability of dam slope is 1.30 when the dam is in normal operation condition. The calculation results show that the safety factor of anti-sliding stability of dam slope at the downstream of the dam meets the requirement of the codes.
3.3 Seepage and Dam slope stability

Three models of steady-state water level, including normal water level, design flood level and check flood level, were established under eight working conditions of concrete proportion of 0, 0.14, 0.29, 0.43, 0.58, 0.71, 0.83 and 1.0 respectively. The water level drop before and after the cutoff wall, single width seepage flow and safety factor of Bishop method were calculated under each working condition.

Figure 5 shows that the decrease of water level before and after the cutoff wall gradually increases with the increase of the ratio when the proportion of concrete is below 0.43, but the increase is not high. In terms of design flood level, the decrease of water level of concrete ratio of 0.43 is only 0.35 m more than that of concrete ratio of 0.29. The decrease of water level before and after the cutoff wall increases sharply and the increment increases gradually when the proportion of concrete increases from 0.43. Compared with the concrete ratio of 0.58, the water level drops 1.2 m more than the concrete ratio of 0.43. Compared with the ratio of concrete to 0.83, the water level decreased sharply to 2.1 m. At the same time, the water level drop before and after the cutoff wall is more than 5 m when the proportion of concrete is more than 0.58 and it shows that the performance of the cutoff wall is good. To sum up, the anti-seepage effect of the anti-seepage wall does not change significantly when the concrete proportion is less than 0.43 and the anti-seepage effect of the anti-seepage wall increases significantly when the concrete proportion is more than 0.43. As for the water level drawdown map before and after the cut-off wall, it is recommended to consider the cut-off wall with the concrete ratio of more than 0.58.

![Figure 4. Downstream slope K=1.568 when the concrete ratio is 0.58.](image)

![Figure 5. Water level drop before and after cutoff wall under various working conditions.](image)
Figure 6 shows that the single width seepage flow under each stable water level is not high. With the increase of concrete proportion, the single width seepage flow is smaller and smaller and the difference is larger and larger. When the concrete proportion reaches above 0.71, the single width seepage flow is only half of that of the concrete ratio of 0. Simultaneously, the single width seepage flow decreases sharply to about 0.2 when the proportion of concrete reaches 1.0. Therefore, in terms of single wide seepage flow, the influence of concrete proportion is not too great. Under the condition that the conditions allow, it is suggested to consider the impervious wall with concrete proportion of more than 0.71.

As shown in Figure 7, the safety factor of Bishop method is greater than 1.30 under all working conditions. At the same time, with the increase of concrete proportion, the safety factor of Bishop method gradually increases, and the increase is originally larger. When the concrete proportion is 1.0, it increases sharply to about 1.6.

Figure 6. Single wide seepage flow under various working conditions.

Figure 7. Safety factor of Bishop method under various working conditions.
4. Conclusions

(1) As for a reservoir in Jiangxi Province, when the proportion of concrete reaches 1.0, the water level drop before and after the anti-seepage wall, the single wide seepage flow and the safety factor value of Bishop method are all close to the best anti-seepage performance and the most stable state of the dam slope.

(2) It is suggested that the concrete anti-seepage core wall should be considered as much as possible when conditions permit. The anti-seepage effect of the anti-seepage wall increases significantly when the proportion of concrete is more than 0.43.

(3) The change of concrete proportion has little influence on the single wide seepage flow and the stability of dam slope. In terms of the anti-seepage performance of the anti-seepage wall, it is suggested to consider the anti-seepage wall with high concrete proportion.

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