Analysis on Seepage Flow and Dam Stability of Ecological Permeable Dam

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Abstract: In this paper, the Geo-studio finite element analysis software is used to establish a variety of dam models to analyze the seepage of permeable dam and the slope stability, the results of seepage data are compared by hydraulic physical model experiment. The results show that the single width seepage flow of the permeable dam is 0.0017398m²/s, which meets the design permeability; the XY rate of seepage of the dam meets the law of permeability coefficient mutation. The minimum safety factor is 1.0388, the most likely slip surface appears in the middle and lower part of the dam body facing the water surface, and the leakage point is above the reservoir in the dam, reinforce this area in advance to prevent seepage damage; the simulation process also showed that dams with similar permeability coefficients are safer and more reliable. These research results have certain reference value for the design and research of permeable dams in the future.

1. Introduction
Ecological permeable dams¹¹ evolved from traditional earth-rock dams and developed a small hydraulic structure that controls non-point source pollution water bodies based on the principles of constructed wetlands and rapid infiltration mechanisms. Water purification is achieved by physical filtration, aquatic plant absorption and microbial degradation, but the key lies in the permeability of the soil in the dam²⁻³. Therefore, we start from the structural design of ecological permeable dam to study the seepage characteristics and stability of the dam itself.

2. Computational theory
The seepage calculation of permeable dam is combined with seepage equation and Darcy's law, and the rigid limit equilibrium method is used for dam stability analysis.

2.1 Finite element calculation method for saturated/unsaturated seepage
\[ \frac{\partial}{\partial x} \left( k_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial z} \left( k_z \frac{\partial h}{\partial z} \right) = C \frac{\partial \theta}{\partial t} \] (1)
Where: \( h(x,y,z,t) \) is the head function to be calculated; \( k_x \) and \( k_z \) are \( x \) and the \( z \) axis is the permeability coefficient in the main axis direction; \( C \) is the water capacity, \( C = \frac{\partial \theta}{\partial h} \); \( \theta \) is the water content per unit volume.

2.2 Analysis and calculation method of slope stability
Swedish circular arc method is the simplest method in slope analysis⁴, which ignores the forces on both sides of soil strip. The safety factor of earth dam is calculated as follows:
$$K_F = \frac{\sum M_{rl}}{\sum M_{st}} = \frac{\sum (W_i \cos \alpha_i \tan \varphi_i + c_i l_i)}{\sum W_i \sin \alpha_i}$$

Where: $M_{rl}$, $M_{st}$ are the anti-sliding moment and sliding moment of a soil strip; $W_i$, $l_i$ are the gravity of a soil strip and the length of the bottom surface of the soil strip; $\alpha_i$, $c_i$ and $\varphi_i$ are the inclination angle, cohesive force, Angle of internal friction.

3. Example calculation

According to the existing river data, the yanghe in an area is 3 meters wide with a daily flow of about 390 m$^3$/d. The river is low all year round, with a daily water level of 2.0 meters and a record high of 2.9 meters, now it is planned to build a permeable dam with a permeability of 435 m$^3$/d on the river. The "three-layer" material is used for the construction of the dam. The preliminary design dam height is 3m, the length of dam bottom is 10.1m, dam crest width is 2m, upstream dam slope ratio $m_1=1.5$, downstream dam slope ratio $m_2=0.7$, the diameter of the drainage pipes of the back dam is $\Phi=20$cm. In the middle of the dam is a concrete box structure, which is used to store water for self purification. From left to right, the pervious dam is composed of permeable filter material layer, middle pool and concrete back dam. The upstream water level is 2.85m, the middle pool water level is 2.0m, as shown in Figure 1.

![Figure 1. The preliminary design of the dam (unit: mm)](image)

| Type: Permeability coefficient | Geotextile + Pebble | Gravel and Sand | Coarse Sand |
|--------------------------------|---------------------|----------------|-------------|
| Value ($\times 10^{-3}$ cm/s)  | 7.8                  | 1.8            | 2.0         |

3.1 Finite element calculation and analysis of ecological permeable dam

The Seep/w and Slope/w modules in Geo-Studio finite element software are used to establish the finite element model I of the dam under the condition that the internal friction angle of the filled soil and its own bulk density are satisfied, as shown in Figure 2.
Figure 2. Finite element model of ecological permeable dam

Using Geo-Studio software to mesh the model in Figure 2 and verify the independence of its mesh. As shown in Table 2. The simulation results show that when the number of grids exceeds 31,000, the calculation results reach a stable state. Therefore, in order to improve the calculation efficiency, this paper finally selects this set of grids with a grid unit number of 31838 to simulate the permeability and stability of the overall structure of the permeable dam.

The finite element permeable dam seepage calculation is to calculate the permeability and seepage stability of the permeable dam according to the designed permeable dam size and the permeability coefficient of the filter material to be used to ensure that the dam meets the requirements of stable permeation [5]. According to the empirical value method, the permeability coefficient of the filter material inside the dam body is preliminarily designed, as shown in Table 1 above. The gravity γ and internal friction angle φ of the three types of gravel measured by the geotechnical test [6] are shown in Table 3.

| Type                  | Heavy γ (kN/m³) | Friction angle φ (°) |
|-----------------------|-----------------|----------------------|
| Geotextile + Pebble   | 20.50           | 31.4                 |
| Gravel and sand       | 18.63           | 30.1                 |
| Coarse sand           | 16.50           | 28.9                 |

According to Table 2 and Table 3, the seepage flow rate of the permeable dam body, the distribution of permeability and total water head in single width of dam, the XY rate change of the dam body base under its seepage conditions, and the slope stability calculation results are obtained, as shown in Figure 3 to Figure 5.

The results of Figure 3 to Figure 5 show that the permeable dam's single-width seepage flow rate is 0.0018775 m²/s (about 486 m³/d), which can meet the preliminary design permeability. The minimum safety factor is 1.0388 and it cannot meet the safety values stipulated in the "Design Code for Rolled Earth and Rock Dams". The XY rate of the dam body base seepage meets the seepage law and conforms to the permeability coefficient mutation law. The most likely slip surface appears in the middle and lower parts of the dam body’s upside surface, the escape point of the dam leakage is above the reservoir in the dam, so these two areas can be reinforced in advance to prevent seepage damage.
On the basis of the calculation of model I, under the premise of satisfying the friction angle and its own bulk density of the filled soil, recombine the filler to establish finite element models II, III, the model differences are shown in Table 4.

| Model type | Filler selection     | Permeability coefficient |
|------------|----------------------|--------------------------|
| II         | Geotextile + Pebble  | $7.8 \times 10^{-1}\text{cm/s}$ |
| III        | Gravel with sand     | $1.8 \times 10^{-2}\text{cm/s}$ |

The simulate results for two models are shown in Figures 6 and 7, it show that model II can satisfy the seepage flow of the channel, while model III cannot. The minimum safety factor also decreases with the decrease of packing severity.

Figure 6. Permeability, total head distribution, slope stability (model II)

Figure 7. Permeability, total head distribution, slope stability (model III)

Figure 8. The relationship between model safety Factor and arc radius

The calculation results of the model safety factor and the detailed data of the position and radius of the sliding surface of the simulated dam body are shown in Figure 8. It can be seen from the figure that the arc radius of the most likely failure surface of the whole dam is about 3m, and the failure location is in the lower area of the dam adjacent to the water surface.
3.2 Hydraulic test of ecological permeable dam

According to Qi Lan’s research on the structure design of permeable dam, it is found that when two or more kinds of filter materials are used, the function of dam body is better. Therefore, hydraulic test is carried out for model I, the physical model is made of plexiglass, and the model is designed by gravity similarity criterion.

| Types          | Permeability coefficient:  |
|----------------|-----------------------------|
| ① Coarse sand  | 2.4×10⁻¹ cm/s               |
| ② Medium sand  | 6.0×10⁻² cm/s               |
| ③ Fine sand    | 6.0×10⁻³ cm/s               |

According to the geotechnical test, the permeability coefficient of 8-18 mesh, 30-40 mesh and 60-10 mesh river sediment is tested, and the final values are shown in Table 5.

The overflow device is set at the upstream water level of 28.5cm to keep the upstream water level of the dam unchanged, and the reservoir water level within the dam is 20cm; After the model was stabilized, several infiltration tests were carried out. The measured results of the single width flow of the dam body are shown in Table 6.

| number | Upstream (cm) | Downstream (cm) | Temperature (℃) | seepage (cm²/s) | Correction factor | Correction value (cm²/s) |
|--------|---------------|-----------------|-----------------|-----------------|-------------------|------------------------|
| 1      | 28.5          | 20.0            | 20.5            | 63.938          | 0.976             | 62.403                 |
| 2      | 28.5          | 20.0            | 20.5            | 63.462          | 0.976             | 61.938                 |
| 3      | 28.5          | 20.0            | 20.5            | 63.750          | 0.976             | 62.220                 |
| 4      | 28.5          | 20.0            | 21.5            | 63.462          | 0.964             | 61.177                 |
| 5      | 28.5          | 20.0            | 21.5            | 64.322          | 0.964             | 62.006                 |
| 6      | 28.5          | 20.0            | 21.5            | 62.174          | 0.964             | 59.936                 |
| 7      | 28.5          | 20.0            | 21.5            | 62.378          | 0.964             | 60.132                 |
| 8      | 28.5          | 20.0            | 21.5            | 62.961          | 0.964             | 60.694                 |
| 9      | 28.5          | 20.0            | 21.5            | 62.792          | 0.964             | 60.531                 |
| 10     | 28.5          | 20.0            | 21.5            | 63.871          | 0.964             | 61.572                 |

It can be seen from table 6 that the average single width seepage flow of the dam body measured by multiple groups of experiments is 61.261 cm²/s. According to the scale model of the single width seepage flow Q=1937.07 cm²/s, compared with the simulated value of 1877.5 cm²/s calculated by finite element method, the single width seepage flow test value is greater than 3.08% of the calculated value. The reason for this error may be due to the certain extra pressure on the dam body during constant water injection upstream of the dam body. But the error is within a reasonable range.

4 Conclusion

The finite element calculation results show that the minimum safety factor of the dam body appears in the lower part of the inlet surface of the dam body and the seepage outlet point is located above the dam body reservoir area. Engineering measures should be taken in both places to prevent leakage from damage. The hydraulic model test for Model I showed that the error between the measured seepage flow and the calculated value of finite element is small, so the dam design is reasonable, which has certain reference value for the design and research of pervious dams in the future.
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