Calculation and Analysis of Earth-rock Dam Seepage Flow Based on FEM

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Abstract. Earth-rock dam is the oldest dam type and is the most widely used type of dam in the world. Because earth-rock dams have the superiority that other dam types do not have, earth-rock dams have a large proportion in China. After the earth-rock dam is built to retain water, it sees a seepage in the dam body. The earth and rock material in the saturated zone is subjected to buoyancy, which reduces the effective weight against sliding. After the dam is immersed in water, the shear strength index of the earth and stone will be reduced, and the seepage force may have an adverse effect on the dam slope. When the seepage flows out of the dam slope, dam foundation or river bank, the dam body may cause piping, fluid and other seepage damage. Therefore, we must carry out the seepage analysis of the dam body, and the finite element method is mainly applied to the seepage analysis of the dam body. This paper uses the APDL language programming of ANSYS software to complete the seepage calculation and analysis of earth-rock dams. This paper uses the post-processing module of ANSYS to view the seepage path, seepage results and wetting line of the earth-rock dam.

1. Introduction
The problem of seepage in actual engineering is very complicated, because many practical problems are not a single medium seepage. Approximate solutions or empirical solutions are often used in practical engineering, but these methods do not give satisfactory answers. This paper attempts to solve this problem using the finite element method. However, due to the complexity of the seepage problem itself, how to simulate the seepage problem accurately and accurately using the numerical simulation method is a process that needs to be continuously improved. In this paper, the general finite element analysis software ANSYS is used as the calculation platform. The mutual comparison between the seepage field and the temperature field is used. Based on the ANSYS temperature field analysis function, the unsteady seepage calculation program is obtained. Through calculation and analysis, this paper conducts a comprehensive study on the stable seepage analysis of earth-rock dams.

2. Project overview
2.1. Earth and rock dam overview
In order to better develop the local agricultural economy, the local government built the dam in order to improve local agriculture without the interference of floods and unnecessary losses caused by floods. After the dam is completed, it will mainly undertake flood control safety.
After field survey, hydrological data collection and flood calculation, the dam is designed as an earth-rock dam whose cross section is an isosceles trapezoid: the top width is 4m, the upstream and downstream slope ratios are 1:2, the total height is 12m, and the bottom width is 52m. The upstream water depth of the dam is 8m, and the downstream of the dam is waterless.

Figure 1. a cross-sectional schematic view of embankment dams

2.2. Safety monitoring
According to the design specification SL44-93 water conservancy and hydropower engineering design flood calculation specification, China's concrete face rockfill dam generally needs deformation and panel deflection and vacancy in the dam, dam body and dam foundation and dam seepage, rockfill stress And monitoring items such as panel stress strain and temperature. The internal deformation monitoring of the dam is mainly oriented to the vertical direction and the direction of the river. There are also projects to monitor the deformation of the river and the monitoring of the leakage. Some projects have attempted to use fiber optic gyroscopes to monitor panel deflection. The safety monitoring automation work of the recent project has also developed rapidly. The safety monitoring work can basically run through the project all the time. The monitoring facilities and the subject project are implemented simultaneously and the monitoring data is collated and analyzed in time, which basically meets the purpose of feedback design and guiding construction. The penetration monitoring of deep overburden concrete face rockfill dams is a major technical problem.

3. Seepage calculation of earth-rock dam

3.1. Permeability coefficient
When using Darcy's law to calculate the seepage, first determine the osmotic pressure coefficient of the soil. The K value is a comprehensive indicator of the seepage characteristics of the reaction soil. The magnitude of the K value depends on many factors, but is primarily related to the properties of the porous medium and the physical properties of the liquid. Because the seepage problem in water conservancy projects is mainly based on water, the physical properties of temperature versus K are negligible. Therefore, the permeability coefficient can be simply understood as a parameter that affects the permeability of the porous medium. There are three main methods for determining the permeability coefficient.

- Indoor measurement method
- Site measurement method
- Experience method

The field measurement method is used in this paper.

The permeability coefficient is shown in Table 1.

| pore pressure/m | permeability coefficient/(m/d) |
|----------------|-----------------------------|
| -10.0          | -4.0                        |
| -9.0           | -3.6                        |
| -8.0           | -3.2                        |
| -7.0           | -2.8                        |
| -6.0           | -2.4                        |
| -5.0           | -2.0                        |
| -4.0           | -1.6                        |
| -3.0           | -1.2                        |
| -2.0           | -0.8                        |
| -1.0           | -0.4                        |
| 0.0            | 0.0                         |

3.2. Seepage calculation in the upstream and downstream sections

3.2.1. Upstream section seepage calculation. This article uses two-stage calculation, as shown in Figure 2.
Figure 2. Two-stage calculation diagram

By replacing the upstream wedge-shaped ABD with the imaginary equivalent rectangle AA'BD, it is considered that the water flow penetrates into the dam from the vertical plane A'B'. The width of the rectangular body is determined by $\Delta S$, and the head loss to the AD section through the rectangular body AA'BD and the wedge-shaped ABD, respectively, should be equal under the action of the same upstream water depth A'B and single width flow. The width $\Delta S$ of the equivalent rectangular body can be determined by the equation (1).

$$\Delta S = H_1 \cdot m_1 \cdot (1 + 2m_2)^{-1}$$  \hspace{1cm} (1)

Substituting the corresponding data into the formula (1), the calculation can be obtained:

$$\Delta S = 8 \times 0.5 \times (1 + 1)^{-1} = 2(m)$$  \hspace{1cm} (2)

Taking the impervious layer at the bottom of the dam as the reference surface, the section is regarded as a gradual seepage. Then use equation (3) to find the average seepage path length.

$$\Delta L = \Delta S + L - m_2 \cdot (H_2 + a_0)$$  \hspace{1cm} (3)

Substituting the corresponding data into equation (3) calculates the obtainable value as in equation (4).

$$\Delta L = 2 + 48 - 0.5 \cdot (0 + 0) = 50(m)$$  \hspace{1cm} (4)

Therefore, the average hydraulic gradient of the upstream section is:

$$J = \Delta H \cdot \Delta L^{-1} = [\Delta S \cdot (\Delta S + L - m_2 \cdot (H_2 + a_0))]^{-1} = H_1 \cdot (\Delta S + l)^{-1}$$  \hspace{1cm} (5)

After the data is substituted, it can be calculated:

$$J = 8 \times (48 + 2)^{-1} = 0.16$$  \hspace{1cm} (6)

According to the Dolby formula, the average permeate flow rate in the upstream section is:

$$V = KJ$$  \hspace{1cm} (7)

Where $K$ is the permeability coefficient.

Substituting data into equation (8) can be obtained:

$$V = -3.2 \times 0.16 = -0.512(m \cdot s^{-1})$$  \hspace{1cm} (8)

The formula of the average cross-sectional area of the dam body in the upstream section:

$$A = 0.5(H_1 + H_2 + a_0)$$  \hspace{1cm} (9)

By substituting data into and calculating, we can get:

$$A = 0.3256$$  \hspace{1cm} (10)

Then the permeate flow rate passed by the upstream section is:

$$q = AV$$  \hspace{1cm} (11)
Substituting data, the value $q$ is obtained:

$$q = -3.2 \times 0.3265 = -1.0449 (m^3 \cdot d^{-1})$$  

(12)

3.2.2. **Downstream segment calculation.** Since the downstream of the dam is waterless, it is not necessary to calculate the seepage flow in the downstream section.

3.3. **Immersion line calculation**

The equation of the wetting line of the earth dam seepage can be directly derived from the formula of the wetting line of the underground trough of the flat rectangular prism. Take the $xoy$ coordinates as shown in Figure 3. Take a cross section at $x$ from the point O, and the water depth is $y$, then:

$$X = x \cdot k \cdot (2q)^{-1} \cdot (H_1^2 - y^2)$$  

(13)

This formula is the saturation line equation of a homogeneous earth dam on a horizontal impervious layer. Set a series of $y$ values, which can be calculated from the above formula to form a series of corresponding $x$-value points into a immersion line. The value of $y$ taken and the corresponding value of $x$ are shown in Table 2.

Table 2. $x$, $y$ values

| $y$ | 0   | 1   | 2   | 3   | 4   | 5   | 6   | 7   |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $x$ | 97.99 | 96.46 | 91.89 | 84.22 | 73.49 | 59.72 | 42.87 | 22.97 |

The data is plotted in the figure to obtain the corresponding immersion line, as shown in Figure 3.

![Figure 3](image.png)

4. **Modeling and analysis based on APDL**

This paper uses unsaturated seepage to calculate. The permeability coefficient is a function of the void pressure and the permeability coefficient function is as follows.

-10.00  -4.0E+00  
-9.00   -3.6E+00  
-8.00   -3.2E+00  
-7.00   -2.8E+00  
-6.00   -2.4E+00  
-5.00   -2.0E+00  
-4.00   -1.6E+00  
-3.00   -1.2E+00  
-2.00   -8.0E-01  
-1.00   -4.0E-01  
0.00    0.0E+00

The first column is the void pressure value (m) and the second column is the permeability coefficient parameter ($10^a (m^3/d)$).

The APDL is used to build a solid model and mesh, and the mesh model of the earth-rock dam is obtained.
The upper and lower total heads of the earth-rock dam are determined according to the working conditions, and the following figure can be obtained.

5. Solving and analyzing

Based on the established finite element model of the earth-rock dam, the static analysis solution of the pre-stress effect “PSTRES, ON” is opened. Then re-enter "SOLUTION" and get the analytical solution.

The convergence error of this calculation takes the default value, and the number of iterations takes 20 times.

The above APDL commands are saved as "*.mac" files and placed in the ANSYS work target folder. Start ANSYS, type "*.mac" at the command line, type enter, and the program will automatically complete the modeling and solving work.

6. Conclusion

There is no special seepage field analysis in ANSYS software, only the temperature field can be used to simulate the seepage field, so there will be some unreasonable factors in the simulation process. Through the above manual calculation and software analysis, the seepage flow of the earth-rock dam can be clearly known. The results of manual calculations and the results of ANSYS software analysis
are not much different. In the modeling process, the finite element model is based on the geometric and material parameters of the structure provided in the original design drawings. Influencing factors can be considered as much as possible in the modeling process, such as the calculation of the upstream and downstream surfaces and the free surface.

The model of each stage of seepage flow of earth-rock dams derived from this paper is based on the initial finite element model of the design. There is no correction based on the measured results of the earth-rock dam test after the completion, so the finite element model needs to be revised in the next study. When the modal analysis of the earth-rock dam is carried out, the convergence problem is found in the calculation of the structural nonlinear problem by the finite element method. To get a more accurate solution, you need to constantly correct your convergence criteria to get better results.

The seepage flow and total head cloud map obtained by post-processing are the main modal parameters reflecting the structural dynamic characteristics, and are the main basis for evaluating the seepage of earth-rock dams. According to the data obtained from the analysis, the seepage characteristics of the earth-rock dam can be better understood, so as to predict possible hazards, prevent in advance and avoid unnecessary losses.

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