Seepage analysis of clay core wall dam based on ABAQUS

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Abstract. The seepage analysis of earth-rock dams is required to define the seepage field as a community of saturated and unsaturated regions. The two complement each other. The motion characteristics of unsaturated seepage are relatively complex, and the influence factors are more than saturated seepage. In this paper, combined with engineering examples, the finite element numerical simulation is used to simulate the variation of the seepage field of the earth-rock dam in saturated and unsaturated seepage, and the wetting line, seepage flow and stress and strain inside the dam are obtained. The data results are reasonable and correct. It has certain reference value in the construction of anti-seepage system of earth-rock dam.

Keywords: Finite element; earth-rock dam; unsaturated; seepage.

1. Introduction
The anti-seepage function is one of the main application functions of earth-rock dams. Because the earth-rock dam is a granular structure, there are large pores between the particles, and there is water permeability. After the water is blocked by the dam, under the influence of the upper and lower water level difference, Water will penetrate downstream through the dam body, dam foundation and dam shoulder, causing leakage of dam body, dam foundation and dam abutment. The seepage not only exerts pressure or floating force on a certain contact surface, but also the soil particles themselves are also affected. The buoyancy and drag force of the pore water flow, the pair of forces and reaction forces, have a certain destructive effect on the soil energy [1], affecting the stability of the dam, so the seepage analysis is a very important content, correct and reasonable Analysis of seepage is the key to ensuring the safe operation of earth-rock dams. The seepage field of earth-rock dam is composed of saturated zone and unsaturated zone. The two are mutually restricted and interconnected, and many influencing factors, rainfall and water level changes can change the active zone of saturated zone and unsaturated zone [2]. In this paper, ABAQUS finite element software is used to analyze the seepage of a clay core wall dam, and the steady seepage condition under saturated-unsaturated conditions is simulated. The downstream escape point, immersion line and seepage flow of the design conditions are calculated.
2. Saturated-unsaturated seepage mathematical model

2.1. Definite condition
When solving the stable seepage equation, the boundary conditions are listed; When solving the unstable seepage equation, the initial conditions and the boundary conditions of the whole process are listed. Based on the fluid mathematical model, it can be divided into the following three types of boundary conditions:

1) The first type of boundary condition is the head boundary condition, assuming the head distribution of the known boundary. The expression is as follows:

\[ h|_{\Gamma_1} = H_1(x, y, t) \]  

2) The second type of boundary condition is the flow boundary condition. Assuming the potential function of the known boundary, the expression is as follows:

\[ \frac{\partial h}{\partial n} |_{\Gamma_1} = -\frac{v}{k} = H_2(x, y, t) \]  

3) The third type of boundary condition is a mixed boundary condition, which defines a linear relationship between the head water head difference and the water level energy, namely:

\[ h + \frac{\partial h}{\partial n} = \beta \]  

In the above formula: \( \alpha \) and \( \beta \) are normal numbers.

2.2. Saturated-unsaturated seepage differential equation
In saturated soil, the forces that cause moisture transfer are gravity and water pressure. In unsaturated soils, the surface water that dominates the transfer of liquid soil water is the surface tension of gravity and water. Richards et al. In 1931, it was proved that the seepage of unsaturated soil is consistent with Darcy's law and continuous equation and saturated soil. If Darcy’s law is substituted into the continuous equation (ignoring the change of total stress during the infiltration process and the deformation of the soil particle skeleton) and using the total head \( h \) as the unknown, when the main direction of the infiltration and the coordinate axis, the differential equation of the seepage dimension of the unsaturated soil Can be expressed as:

\[ \frac{\partial}{\partial x} \left( k_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial h}{\partial y} \right) = \frac{\partial \theta_w}{\partial t} \]  

In the formula, \( k_x, k_y \) are the permeability coefficients in the x and y directions respectively; \( \theta_w \) is the volumetric water content; \( h \) is the total head; \( t \) is time. Let \( y \) be the head of the position, then: \( h = \frac{u_w}{\gamma_w} + y \) If \( mw \) is the slope of the soil water characteristic curve, then: \( \frac{\partial \theta_w}{\partial t} = m_w \frac{\partial u_w}{\partial t} = m_w \gamma_w \frac{\partial (h - y)}{\partial t} \). Formula (4) can be written as:

\[ \frac{\partial}{\partial x} \left( k_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial h}{\partial y} \right) = \frac{m_w \gamma_w \partial (h - y)}{\partial t} \]  

Since \( y \) is a constant, the equation (5) can be simplified as:

\[ \frac{\partial}{\partial x} \left( k_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial h}{\partial y} \right) = \frac{m_w \gamma_w \partial h}{\partial t} \]
The above formula is a two-dimensional saturated-unsaturated seepage equation. When calculating stable seepage, \( \frac{\partial h}{\partial t} = 0 \), then:

\[
\frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial h}{\partial y}\right) = 0
\] (7)

It can be seen from equation (7) that the permeability coefficient in unsaturated soil is no longer a constant, but a function of water content. This function is called the permeability coefficient function of unsaturated soil. Therefore, in order to carry out stable seepage analysis, it is necessary to know the permeability coefficient function of the material, including the permeability coefficient function of the negative pore nip, to obtain a stable seepage field of saturated-unsaturated soil [3].

3. Model establishment

This paper analyzes the seepage of the proposed Shizihe Reservoir in the southern mountainous area of the central hinterland of Zhuxi County [5]. The reservoir mainly includes barrage, spillway, tunnel, etc. The storage capacity is 0.17 billion m\(^3\) and the irrigated area is 5300 mu, according to the reservoir level. Dividing the standard, the hub belongs to the III and other projects, and the scale of the project is medium. The hub task is based on power generation, with various development targets such as flood control, irrigation, and human and animal drinking.

3.1. Model data

The dam is a clay core wall dam. The dam crest is 8m wide, the dam bottom is 348.76m wide, and the dam height is 59m. There are two-stage horse tracks on the upper reaches, 2m wide, and the dam slope below the 2nd level is 1:3. The above dam slope is 1:2.75, there is a rockfill slope on the upstream slope, and two grades on the downstream. The width is 2m. The dam slope below the 2nd grade road is 1:2.75. The upper dam slope is 1:2.5. The downstream slope is provided with turf slope protection and downstream. It has a drainage prism with a top width of 1.5m and a height of 4.5m. The top of the core wall is 3m wide, the top elevation is 692m, and the slope on both sides is 1:0.15. There is a filter layer and a transition layer. The reservoir design flood level is 56m and the check flood level is 57.2m.

![Figure 1. Diagram of Cross Section of Earth-Rock Dam](image)

3.2. Calculation parameter

The model consists of three parts, the dam body, the core wall and the prismatic drainage. The dam body is made of gravel mixture, the core wall is made of clay, the middle and lower reaches is set with medium fine sand filter layer, and the drainage prism is made of rockfill. Each part is treated as a homogeneous material, and the physical and mechanical properties of the specific materials are shown in Table 1.
Table 1. Physical and mechanical indicators of dam body soil

| Material               | Elastic Modulus (Mpa) | Wet density (t/m³) | Permeability coefficient (m/s) | Poisson's ratio |
|------------------------|-----------------------|--------------------|--------------------------------|-----------------|
| Gravel mixture         | 55.6                  | 2.32               | 3.5x10⁻⁶                      | 0.25            |
| Heart wall clay        | 32.5                  | 1.96               | 1.157x10⁻⁸                    | 0.3             |
| Medium fine sandstone  | 60.2                  | 1.99               | 3.5x10⁻⁵                      | 0.4             |
| Rockfill               | 100                   | 2.02               | 0.75                           | 0.3             |

The effect of saturation on the permeability coefficient is considered within ABAQUS with a reduction factor $k_s$. If there is an unsaturated seepage ABAQUS/Standard default when the saturation $S_r < 1$, $k_s = (S_r)^3$; when $S_r \geq 1$, its permeability coefficient $k = k_s k$. The relationship between pore water pressure and volumetric water content corresponding to unsaturated soil can be described by the soil water characteristic curve, as shown in Fig.2; the relationship between pore water pressure and permeability coefficient can be determined by the permeability coefficient function. Shown. The initial state assumes a saturation of 1 and an initial void ratio of 1.0.

$$k_w = \frac{k_s[1-(\alpha \psi^n-1)\cdot(1+(\alpha \psi)^n)^{-m}]^t}{(1+(\alpha \psi)^n)^{m/2}}$$

(8)

Figure 2. Soil-water characteristic curve

3.3. Boundary conditions

The boundary has a mechanical boundary and an infiltration boundary, wherein the mechanical boundary includes a stress boundary and a displacement boundary. Stress boundary: Take the gravity field as the initial stress field, and the upstream and downstream water surface slopes are subjected to hydrostatic pressure, that is, the head load, which is applied to the model in the form of pore water pressure. Displacement Boundary: For ease of calculation, the bottom of the model is assumed to be a fixed boundary, constraining horizontal displacement and vertical displacement, and the upstream and downstream surfaces are free boundaries. Infiltration boundary: In order to facilitate the calculation, the bottom of the model is assumed to be impervious to the water boundary, and the waterfront side of the slope and the rock mass are freely permeable. Using the CAE module in ABAQUS, a two-dimensional...
model of the earth-rock dam is established. When the grid is divided, the unit type is CPE4P, which is the pore pressure unit with osmotic pressure/displacement coupling.

3.4. Calculation conditions
The working condition selected in this paper is to check the water level condition, that is, the check flood level is 57.2m. Since the check water level is the highest water level of the dam, it is more representative and the calculation result is more reference. If the water level is checked Seepage and stress and strain are reasonable. We have reason to think that the seepage of the designed water level or dead water level is normal, which means that the seepage risk of this reservoir is small and the reservoir is safe.

4. Analysis of calculation results

![Figure 3. Saturation distribution](image)

As can be seen from the Fig. 3, the yellow portion is a region with a saturation of 1, the yellow region is above, the saturation is less than 1, and the upper the saturation, the smaller the saturation.

![Figure 4. Pore pressure distribution map](image)

It can be seen from the Fig.4 that the pore pressure at the bottom of the water-facing surface is the largest, and the upward pore pressure is gradually reduced. At the interface where the pore pressure is 0, that is, the free water surface, there is a steep drop process at the core wall, and finally the drainage prism is passed.

The graph and the saturation profile are roughly the same, but the pore pressure in the region with saturation 1 is different, while in the region where the pore pressure is negative, the two are positively correlated.
The Fig.5 and Fig.6 shows the stress distribution in the x-axis and y-axis directions. The negative value is the pressure and the positive value is the tensile force. As can be seen from the figure, in the upstream part, the stress on the dam slope surface is the largest in the x and y-axis directions. The lower the stress, the less stress is at the ends of the core wall.

According to Fig. 7, the displacement distribution map shows that the displacement of the dam body at the top reaches the maximum, up to 0.5851 mm, and the lower the displacement is, the smaller the displacement is. Because we assume that the base surface is fixed, the displacement at the bottom of the dam is 0. In practice, the displacement of the dam foundation exists, but the smaller the displacement does not affect our seepage calculation.
See Fig. 7 above for the seepage flow of the dam at the RVF toolbar. From the information in the figure, the seepage flow through the rockfill prism is $0.4738 \times 10^{-3}$ m$^3$/s, which is $4.738 \times 10^{-8}$ m$^3$/s.

The above Fig. 9 is the calculation of seepage flow using the see/w software in GeoStudio software. This figure is the distribution map of the immersion line of the dam. It can be seen that the saturation line calculated by the ABAQUS seepage is basically the same, and the single width calculated by GeoStudio. The seepage flow rate is $1.3939 \times 10^{-7}$ m$^3$/s, which is also consistent with the calculated value of ABAQUS.

5. Summary
The calculation analysis shows that:

(1) The earth-rock dam has three parts. The materials and physical and mechanical properties of different parts are different. The analysis shows the wetting line and seepage flow of the earth-rock dam at the check water level. Under the saturated-unsaturated seepage field, the seepage flows through the clay. The immersion line of the core wall drops sharply, the pore pressure above the immersion line is negative, the following is positive, and finally the escape point is at the rockfill prism and is discharged through the rockfill prism.

(2) According to the stress and displacement distribution of earth-rock dams, the displacement at the top of the dam reaches the maximum, up to 0.5851 mm, the smaller the downward displacement, the displacement at the bottom of the dam is 0. For the stress distribution, the stress on the water-facing surface is reached. The largest, the lower the stress becomes smaller.
(3) The seepage flow can be directly calculated from the finite element calculation results. The seepage flow of the earth-rock dam is $4.738 \times 10^{-8} \text{m}^3/\text{s}$, which is basically the same as that calculated by GeoStudio, and because of the seepage analysis with GeoStudio, there is no Taking the filter layer on both sides of the core wall into consideration, the calculated seepage flow is different from the actual value. The earth dam model established by ABAQUS solves the problem of the filter layer, and the calculation result is more than the actual value.

According to the existing researches, when using finite element software for seepage analysis, there is a fundamental difference between saturated seepage and unsaturated seepage. Therefore, the saturated-unsaturated seepage model of the calculation model used in this paper not only reflects the seepage water movement in the saturated region. It also reflects the seepage in the unsaturated zone[7], and the numerical simulation results of the seepage are more in line with the actual situation. According to the calculation results of the finite element software, we can preliminarily believe that the risk of seepage in the dam is small and within the acceptable range of engineering safety.

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