Finite Element Analysis on Earth-rock Cofferdam Behavior during Pumping and Drainage of Foundation Pit

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Abstract. The drawdown velocity of foundation pit water level in existing projects is mostly determined empirically, and the influence of water level drawdown velocity on the seepage field and stress field in the weir body is not fully considered. The water level change of the foundation pit is an important factor affecting the stability of the cofferdam. Therefore, it is of great practical significance to study the variation law of seepage field and stress-strain field of cofferdam during the pumping process of foundation pit, to accurately judge the stability of cofferdam slope and to formulate reasonable pumping and drainage scheme. Based on the 1th temporary earth-rock cofferdam of Yongning Water Conservancy Project, the nonlinear finite element method is used to calculate the spatial-temporal evolution of seepage field and stress-strain field of earth-rock cofferdam under different drawdown velocity of water level. The overall deformation of the cofferdam, the shear failure and instability characteristics of the slope, and the influence of water level changes on the stability of the cofferdam slope are analysed. The results show that the distribution of unsaturated zone and negative pore pressure zone is basically the same. The excessive water level drawdown velocity is easy to break the balance between the seepage field and the water level fall time, resulting in the rise of saturation line height and the increase of the upper bending rate. The effect of seepage control is weakened, and the stability of the slope is poor. The shear deformation of the cofferdam slope develops from the foot of the slope and extends to the crest of the cofferdam until it runs through. At the same time, local plastic deformation occurs at the foot of the outer stone slag berm, and the maximum deformation transits to the foot of the inner slope. Under the action of seepage force, the stability of the inner slope is always smaller than that of the outer one; the change of water level drawdown velocity is very sensitive to the stability of the slope, when the drawdown velocity is greater than the critical velocity, the stability of the slope decreases sharply. Combined with the characteristics of earth-rock cofferdam, on the basis of satisfying the stability of cofferdam, the drawdown velocity of water level should be controlled within 1.28m/d. The research results of the thesis have reference significance for the selection of pumping speed of foundation pit similar to earth-rock cofferdam.

1. Introduction
In the construction period of water conservancy and hydropower project, in order to carry out foundation pit construction work in time, rationally formulate the foundation pit water level drawdown velocity to coordinate the construction period and the slope anti-sliding stability relationship, and the
domestic combined engineering practice experience has established the allowable control range of the water level drawdown velocity of the earth and rock cofferdam foundation pit. However, due to the lack of theoretical basis, the engineering experience tends to be conservative, the structure and type of cofferdam are diverse, the design data is rough and the experimental conditions are complex. The anti-sliding safety evaluation of earth-rock cofferdam has not yet formed a unified standard [1-2]. The domestic scholars represented by Ren Dachun et al [3-10] compiled a three-dimensional finite element calculation program, and applied the saturated-unsaturated conditional seepage model to the stability analysis of the impervious core wall with defects for the first time. The earth-rock cofferdam has preliminarily explored the characteristics of the seepage field and the stability mechanism of the seepage field under the effect of stable seepage and fluid-solid coupling. The factors such as the form and depth of the cut-off wall and the change of nonlinear materials have been considered. The characteristics of pore water pressure, saturation line height and osmotic slope during operation are combined with the rigid body limit equilibrium method to evaluate the stability of the slope under the seepage, and the optimization scheme of the seepage control system is provided. The theory of unsteady seepage is applied. The influence law of the water level change of the foundation pit on the seepage field and stability of the cofferdam during construction period is further analysed, which lays a foundation for the research and application of the foundation pit pumping speed during the construction process.

Although the numerical method has been widely used in the analysis of solving the problem of seepage stability of complex geotechnical slopes [11-17], the problem of the influence of the water level change of the foundation pit on the stability of the slope has not been studied in depth. The stability analysis of the earth-rock slope with coupling effect considering the unsteady seepage-stress is very little. The limit equilibrium method can’t reflect the overall deformation and plastic penetration process of the slope. Under the condition of satisfying the stability of the slope and the construction period, there is no exact method for the critical speed of the foundation pit to do precise prediction.

In order to ensure the safety and stability of the slope during the pumping of the foundation pit and meet the minimum construction period, this paper considers the influence of heterogeneous soil permeability anisotropy and matrix suction on permeability based on the unsteady seepage-stress field coupling theory. The finite element method is used to study the seepage characteristics of cofferdam under different pumping speed conditions. The overall strength reduction method based on field variables is used to solve the stability coefficient of the temporary earth-rock cofferdam in the first stage of Yongning Water Conservancy Project to determine the maximum deformation position and potential sliding surface, objective stability analysis and evaluation of the slope, in order to provide theoretical guidance and reference for the reasonable selection of actual engineering foundation pumping speed.

2. Basic equations and fluid-solid coupling theory

2.1. Basic equations

For the unsteady seepage with free surface, the volume of soil compression or elastic release caused by the decrease is much smaller than that of the free surface drop and the compressibility of soil and water body can be neglected [18]. For unsaturated soils, the permeability coefficient is a function of volumetric water content or matrix suction. That is, \( k = k_i(\theta)k_f \) when Darcy’s law is generalized to anisotropic permeation, the basic equation for saturated-unsaturated seepage can be obtained:

\[
\frac{\partial}{\partial x}(k_i(\theta)k_z\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(k_i(\theta)k_y\frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(k_i(\theta)k_z\frac{\partial h}{\partial z}) = n \frac{\partial S_w}{\partial t}
\]  

(1)

\( k_i, k_f \) is saturated permeability coefficient(m/s) in direction \( x, y, z \); \( k_f \) is the ratio of the unsaturated permeability coefficient to the saturated permeability coefficient. For the unsaturated zone, there are \( 0 \leq k_i \leq 1.0 \); \( n \) is porosity; \( S_w \) is saturation; \( \theta \) is volumetric water content.
Considering the mathematical model describing the flow, the boundary conditions of the solution include the head boundary, the flow boundary and the mixed boundary, which can be expressed as

\[
\begin{align*}
&h \big|_{\Gamma_1} = h_1(x, y, z, t) \\
&\frac{\partial h}{\partial n} \big|_{\Gamma_2} = -\frac{v}{k} = f(x, y, z, t) \\
&\frac{\partial h}{\partial n} \big|_{\Gamma_2} = f(x, y, z, t) \geq 0, \forall \Gamma_1 = 0
\end{align*}
\]

where \( h_1 \) and \( h \) are known heads (m) of seepage field and similar boundary conditions respectively, where \( h_1 \) is a function of spatial coordinates and time.

### 2.2. Coupled mechanical mechanism of seepage-stress field

When there is seepage potential or head difference in porous geotechnical medium, the seepage force along the flow direction is generated in the rock soil, and the stress field and displacement field are changed. The effect of the penetrating force on the geotechnical medium can be calculated according to the volumetric force of the continuous medium and the penetrating force and the hydraulic gradient. The permeation volume force of the unit is converted into the external load of the equivalent node by the formula (3) [19].

\[
\{F_s\} = \int_{\Omega_s} [N]^T \begin{cases} f_s \end{cases} dxdydz
\]

\[
\{\Delta F_s\} = \int_{\Omega_s} [N]^T \begin{cases} \Delta f_s \end{cases} dxdydz
\]

\{F_s\} is the equivalent nodal force (N), \{\Delta F_s\} is the equivalent nodal force increment (N), \([N]\) is the unit function, \( f_s, f_y \) and \( f_z \) are the components of seepage force in the direction of \( x, y \) and \( z \), respectively.

According to the principle of effective stress of porous media, the change of stress state of geometrical will change its pore ratio and porosity, causing the permeability of soil, ie the change of permeability coefficient, further affecting the flow and pressure distribution of pore fluid, so the infiltration of soil The coefficient can be expressed as a function of the stress state, ie: \( k = k(\sigma_{ij}) \)

### 2.3. Stress-seepage coupling control equation

#### 2.3.1. The equilibrium equation

Assuming that the saturated-unsaturated rock mass is a continuous medium, and the soil particles and water are incompressible. At a certain moment, the virtual work of the rock and soil and the forces acting on the rock and soil (physical and lateral forces) the virtual work produced is the same. According to the potential energy variation theory and the Biot effective stress principle, the equivalent integral form of the unsaturated soil stress balance equation can be obtained [14, 20].

\[
\int_{\Omega} \delta \epsilon^T \sigma D_{\nu} \frac{\partial \epsilon}{\partial t} dV - \int_{\Omega} \delta \epsilon^T M(s + C_\nu u_\nu) \frac{\partial u_\nu}{\partial t} dV = \int_{\Omega} \delta u^T \frac{\partial f}{\partial t} dV + \int_{\partial \Omega} \delta u^T \frac{\partial p}{\partial t} dS
\]  

(4)
\(D_{ep}\) is an elastic-plastic matrix; \(M\) is a unit array in normal stress; \(\delta\varepsilon\) and \(\delta u\) are virtual displacement and strain; \(t\) is surface force, \(f\) is physical force; \(s\) is saturation; \(u_w\) is pore water pressure; \(C_s = \frac{\partial s}{\partial u_w}\) is the change rate of unsaturated soil saturation to matric suction, which can be obtained from the soil-water characteristic curve.

2.3.2. The continuous equation. Considering a non-saturated soil unit. According to the conservation of mass, the amount of water flowing into the volume during the time should be equal to the increase of the internal water storage. The fluid seepage is described by Darcy's law and introduced into the hole. The pressure boundary condition is directly introduced into the finite element equation as a forced boundary condition. Combined with the seepage head, the divergence theorem can be used to obtain the equivalent integral form of the saturated-unsaturated seepage control equation.

\[
\int_v \nabla (\delta u_w) \kappa \nabla \left( \frac{u_w}{\gamma_w} + z \right) dV + \int_v \delta u_w \left( s \frac{\partial \varepsilon}{\partial t} + n C_s \frac{\partial u_w}{\partial t} \right) dV + \int_s \delta u_w q d\Gamma = 0
\]

\(\nabla A\) is Hamiltonian operator, \(\nabla \equiv \frac{\partial}{\partial x} i + \frac{\partial}{\partial y} j + \frac{\partial}{\partial z} k\); \(\delta u_w\) is variation of pore pressure function; \(\gamma_w\) is water gravity; \(z\) is position head in gravity direction; \(n\) is porosity; \(q\) is water flow through boundary in unit time.

2.4. Finite element solution format of governing equations

For a saturated-unsaturated porous continuum, the finite element is discrete with a certain type of element, with the displacement, strain and pore pressure as unknowns, the structural unit node variable interpolation function, simultaneous (4), (5) Establish a coupled mathematical model, and the finite element format of the stress-seepage coupling control equation is

\[
\begin{bmatrix}
K & L \\
K & S
\end{bmatrix}
\begin{bmatrix}
\dot{a} \\
\dot{P}_w
\end{bmatrix}
= \begin{bmatrix}
0 & 0 \\
0 & H
\end{bmatrix}
\begin{bmatrix}
a \\
P_w
\end{bmatrix}
= \begin{bmatrix}
\dot{F} \\
\dot{P}
\end{bmatrix}
\]

\[
K = \int_v B^T D_{ep} B dV, L = -\int_v B^T M \left( s + C_s u_w \right) \tilde{N} dV, \dot{F} = \int_v N^T \frac{\partial f}{\partial t} dV + \int_s N^T \frac{\partial P}{\partial t} dS, \\
\tilde{K} = \int_v N^T s M^T B dV, S = \int_v n C, N^T \tilde{N} dV, H = \frac{1}{\gamma_w} \int_v k \nabla \tilde{N} \nabla \tilde{N} dV,
\]

\[
P = -\int_v k \frac{\partial \tilde{N}^T}{\partial z} dV - \int_s \tilde{N}^T q dS
\]

3. Project Overview

The Yongning Water Conservancy Project is located at the Niwan Peninsula in the lower reaches of the Yongjiang River in Nanning. It is a large (2) type water conservancy project, including a barrage, a 13-hole dam, a power house and an access road, with a total installed capacity of 57.6 MW and normal water storage at 67m, the barrage project spans the Yongjiang River. From the right bank to the left bank, the joint project of earth dam, joint gravity dam and main plant is arranged in sequence. Two sections of three-stage diversion are adopted. The first phase requires rapid construction and temporary water retention during dry season. The cofferdam uses a widened narrow river bed for diversion and navigation, and builds a first-stage cofferdam on its backwater side to provide dryland construction conditions throughout the year (Figure 1). In the second and third phases, the main
construction of the 9-hole overflow weir, using the completed 4-hole overflow dam diversion and ship lock navigation (Figure 2).

Figure 1. Temporary cofferdam design floor plan

Figure 2. Plan layout of the second stage cofferdam construction

The first-stage temporary earth-rock cofferdam is a key project to ensure the foundation excavation of the first-stage construction, four-hole overflow dam and main building. The axis is from about 350m on the right bank upstream of the dam axis to the dam axis. The downstream right bank is about 320m away from the dam line, and the water depth is about 14m~18m. The sand gravel layer of the alluvial deposit at the bottom of the riverbed is about 1.5m thick, and the riverbed is relatively flat. The underlying bedrock is dominated by limestone and dolomitic limestone, with thick layered structure, uniform lithology and good integrity.

Under the unfavourable conditions that the material source does not fully meet the underwater filling requirements, the construction period is not enough to find the source of materials, and there is no precedent for the construction of similar projects at home and abroad, considering the safety of navigation on the water side of the river, after research and analysis, the Yongning Water Conservancy

The first phase of the temporary cofferdam structure of the hub has undergone major adjustments, using the surrounding stone slag berm, the additional sub-berm of the crest, the central jet grouting anti-seepage wall and the cofferdam structure of the backwater-filled clay combined with anti-seepage (Figure 3). The maximum height of the cofferdam is 18.12m, the elevation is 66.40m, and the design water level is 64.62m. The cofferdam is filled with the construction technology of the non-rolling earth and stone mixture.

Figure 3. Schematic diagram of typical section material of temporary cofferdam
4. Model generalization and finite element analysis model

4.1. Grid model
Calculation range: For the first-stage temporary cofferdam geometric model, the intersection of the dam axis and the axis of the crest of cofferdam is taken as the coordinate origin, the longitudinal cofferdam is on the water-facing side as the X-axis positive direction, and the vertical upward is the Z-axis positive direction. The Y axis is determined by the right hand rule. In order to reduce the boundary effect and improve the accuracy of the calculation results, the calculation is carried out from the upstream to the downstream along the Y-axis direction, with a total length of 896.0 m (Figure 4); along the X-axis from the backwater side of the foundation pit to the water surface of the berm is nearly 4 times wide and covers the entire riverbed and the bank slopes on both sides, totaling 396.0m. The depth of the rock is 101.3m below the surface of the foundation along the Z axis. The top and bottom elevations of the model are respectively 73.0m and -50.0m.

Grid model: In the process of foundation pit pumping, the stability of the slope structure under the coupling of unsteady seepage-stress field is mainly investigated. For the temporary cofferdam, riverbed and slope soil, the displacement/pore pressure coupling element with linear pore pressure distribution and first or second order displacement distribution function is adopted to simulate the transient flow of saturated-unsaturated fluid in porous media.[20]. In addition to the 4-node tetrahedral coupling element (C3D4P) at the upstream diaphragm and the longitudinal joint, the 8-node hexahedron coupling element (C3D8P) is used. The finite element model is shown in Figure 5. The total number of cells is 282,319 and the total number of nodes is 280,664.

Boundary conditions: The initial saturation of the model is set to 1.0, and different pore ratio parameters are assigned as initial conditions according to different materials. The bottom and surrounding of the model are the normal constraints of the surface of the vertical bedrock in the same direction (X, Y, Z) with the origin coordinates. By default, it is impervious boundary; the inner side of the cofferdam, the slope of the water-facing side and the surface of the riverbed are the boundary of the head and the pressure of the pores. The boundary of the free slope is added to the inner slope, and the height of the inner head and the pore pressure are function of coordinates and time.

4.2. Material parameters

4.2.1 Mechanical Models and Parameters. The Mohr-Coulomb constitutive model (referred to as the M-C model) can better describe the mechanical behaviour of soil and other discrete materials.
According to the deformation of the carcass during the pumping period and the instability of the slope, the soil can be approximated as an ideal elastoplastic material. In order to avoid the cumbersome calculation and slow convergence caused by the sharp angle of the MC yield surface, the extended classic MC model is used to simulate the deformation behaviour under hydrostatic load and seepage-stress coupling.

The cofferdam materials mainly include clay, pebbly clay and berm filled with block stones. The river bed is thinner and mainly composed of limestone. The physical and mechanical parameters of the soil layer in the site are shown in Table 1.

Table 1 Recommended values of main indicators for soil layers in the site area

| Parameter                  | Dry unit weight / kN·m⁻³ | Porosity/n | Compressive modulus / MPa | Internal friction angle /° | Cohesion /kPa |
|---------------------------|--------------------------|------------|----------------------------|---------------------------|---------------|
| Pebbly clay               | 17.4                     | 0.374      | 6.9                        | 25                        | 22.0          |
| Berm Block Stone          | 22.5                     | 0.500      | 400.0                      | 30                        | 0             |
| Concrete                  | 24.5                     | 0.015      | 20000.0                    | 40                        | 1200.0        |
| Limestone                 | 27.0                     | 0.048      | 17200.0                    | 46                        | 2720.0        |

4.2.2 Permeability parameters of unsaturated soil. The pore water of the soil seeps continuously as the water level of the foundation pit decreases, and the weir body transitions from saturated to unsaturated, forming a saturated-unsaturated region on the slope of the clay. The saturated soil permeability coefficient can be regarded as a constant (Table 2). For the unsaturated medium, the liquid medium-gas two-phase coexist, the ability of the porous medium to transport fluid is weakened, and the permeability coefficient is not constant, but a function of saturation [21]. According to the cumulative distribution of soil particles (Table 3), considering the orthotropic anisotropy of clay seepage, the empirical model [22] is used to estimate the soil water characteristic curve (Figure 6), and the relationship between permeability coefficient and pore water pressure of unsaturated clay are calculated. (Figure 7).

Table 2 Material permeability coefficient of the site

| Parameter                  | Pebbly clay | Berm Block Stone | Concrete | Limestone |
|---------------------------|-------------|------------------|----------|-----------|
| Permeability coefficient k/ ( m/s ) | horizontal 5.0x10⁻⁶ | 1.0x10⁻⁵ | 1.22x10⁻¹⁰ | 1.2x10⁻⁹ |
|                           | vertical    4.6x10⁻⁷ |           |          |           |

Table 3 Test soil particle size distribution

| Particle size /mm | Component | Proportion /% |
|-------------------|-----------|---------------|
| 60–2              | Gravel    | 7.15          |
| 2–0.075           | Sand      | 15.1          |
| 0.075–0.005       | Silt      | 49.2          |
| <0.005            | Clay particle | 28.55        |

4.3. Calculation of working conditions and water level changes Simulation of cofferdam

Foundation pit pumping is a complex unsteady seepage process. Considering the construction schedule control, the initial drawdown velocity range and the maximum specified in [2] are not more than 1.5m/d. According to the 0.5m/d gradient, the gradient is increased and decreased, and there are 6 kinds of calculation conditions (Table 4). Due to the large height of the longitudinal weir and the deep water level of the foundation pit, the risk of collapse of the longitudinal slope during pumping is relatively higher, and the riverbed in the longitudinal section is relatively flat. In order to facilitate the
analysis of the deformation of the earth-rock cofferdam and the development of the slope, the section of weir body and river bed at dam axis site is selected as typical seepage section, and the position of inner weir top and slope foot is selected as displacement characteristic point (Figure 8).

Firstly, the gravity, static water load and pore water pressure are applied to the cofferdam and the foundation soil respectively. The initial stress level and the stress coupling field of the foundation pit with no displacement are generated by the automatic stress balance method. The static water load and the pore water pressure are respectively reduced with time. The linear function relationship from small to zero simulates the seepage change and the state of force deformation of the cofferdam in the process of water level drop in the foundation pit.

| Working condition | Drawdown velocity/(m/d) | Drainage time/d | Water level /m |
|-------------------|-------------------------|-----------------|----------------|
|                   |                         |                 | Initial | End    |
| 1                 | 0.5                     | 30.0            | 63.50    | 48.50  |
| 2                 | 1.0                     | 15.0            |          |        |
| 3                 | 1.5                     | 10.0            |          |        |
| 4                 | 2.0                     | 7.5             |          |        |
| 5                 | 2.5                     | 6.0             |          |        |
| 6                 | 3.0                     | 5.0             |          |        |
4.4. Finite element strength reduction method
When using the finite element strength reduction method to analyse the slope stability, it is not necessary to assume the slope sliding form and position, and use the field variable to establish the function relationship between the incremental step and the material parameter. The shear strength of soil can automatically be reduced to the ultimate failure of slope, and the position of sliding surface and the reserve safety factor of slope strength can be obtained directly. The expression is:

\[ c' = \frac{c}{F_i} \]  

\[ \phi' = \arctan \left( \frac{\tan \phi}{F_i} \right) \]  

\( c \) and \( \phi \) are the shear strength that the soil can provide; \( c' \) and \( \phi' \) are the shear strength needed to maintain equilibrium or the actual exertion of the soil; \( F_i \) is the strength reduction factor.

The key to the analysis of slope stability by strength reduction method is the correct judgment of the calculation results, and then whether the slope body reaches the critical failure state, and the selection of the reduction range and the criterion is very important [16]. Since the cofferdam is composed of heterogeneous soil materials, the reduction range has a great influence on the safety factor of the slope. According to the concept of “cohesion ratio” proposed in [17], the cohesive soil and the bedrock are sticky. The ratio of the bunching force is much less than 1, and it is more reasonable to reduce the overall strength of the cofferdam. Considering the applicability and simplicity, combined with the literature [18], the jointability of the characteristic part displacement abrupt combined with the plastic zone is used as the slope instability criterion to analyse the cofferdam deformation law and the plastic zone distribution, and then the minimum slope safety factor is obtained.

5. Characteristics of seepage field in foundation pit dewatering
During the process of the water level drop of the foundation pit, the seepage field in the earth-rock cofferdam is non-constant, and the carcass is mostly filled with clay, and the permeability is poor. Over-pumping speed makes it difficult to dissipate excess pore water pressure in the cofferdam and aggravates the seepage stability of the cofferdam. Therefore, it is particularly important to analyse the effects of different pumping speed conditions on saturation, pore water pressure and saturation line distribution of the cofferdam in different periods.

5.1. Saturation distribution
Due to the suction of the soil matrix, the unsaturated zone is mainly distributed near the crest of weir. The saturation of the soil changes from top to bottom, and increases with the height, forming a clear boundary with the saturated zone. With the seepage prevention wall as the centre of the cofferdam, when the drawdown velocity is less than 1.0m/d, there is a local unsaturated zone at the top of the outer clay, and the saturated boundary line of the inner clay is relatively low, and the change from the inside to the outside is approximate flat (Figure 9(a) to (b)). When the drawdown velocity is greater than 1.5m/d, the pore water can’t be discharged in time, the unsaturated area on the top of the outer clay gradually disappears, the saturation gradient is dense and gradually increases, and the position of the inner saturated boundary slightly increases with the increase of the speed and the degree of upward bending increases, and the change approximates the inclined curve. (Figure 9(c) to (f)).

5.2. Pore water pressure
It can be seen from Figure 10, consistent with the distribution of unsaturated zone, the negative pore pressure is mainly concentrated near the crest near the inner clay, the pore pressure increases with the height and increases with a certain gradient, due to the anti-seepage wall resistance effect in the seepage, the gradient of the pore pressure difference on both sides is larger, and the drop is particularly
significant. The contour of the pore pressure below the bedrock tends to be gentle. The zero pore pressure contour is used as the saturation line. When the drawdown velocity is less than 1.0m/d, the seepage field change is consistent with the water level fall time. The saturation line height is low and the change is very slow (Figure 10(a)–(b)). When the drawdown velocity is greater than 1.5m/d, the seepage field changes behind the water level drop time, and the water retention of the clay, as the water level drawdown, the lag time will prolong, causing the highest point of the saturation line to fall behind the water level decline rate, infiltration The line rises slowly with the increase of pumping speed, and the curvature of the free surface of the seepage increases gradually, and the hysteresis effect is more significant (Figure 10(c)–(f)).

5.3. Total head distribution and osmotic slope
The analysis can be obtained from Figure 11. The total head value of the stone berm in the water surface is constant. Under different pumping speed conditions, the total head change of the weir body

Figure 9. Distribution of saturation of earth and rock cofferdam
At the end of the foundation pit drainage, the water level elevation is reduced from 63.5m to 48.5m.

Figure 10. Pore water pressure distribution of earth and rock cofferdam (unit: Pa)
At the end of the foundation pit drainage, the water level elevation is reduced from 63.5m to 48.5m.
is mainly concentrated near the seepage prevention wall. With the increase of the depth of the seepage wall, the osmosis slope gradually increases, and the penetration slope of the wall deep into the bedrock is the largest, and the effect of seepage control is more obvious. However, as the water level slows down, the hysteresis effect increases, and the seepage slope at the same position of the seepage prevention wall decreases continuously, and the effect of seepage control is weakened, which is not conducive to giving full play to the barrier effect of the seepage wall.

6. Stability analysis of cofferdam slope
At the same time as the water level of the foundation pit decreases, the hydrostatic pressure acting on the slope of the cofferdam also decreases. If the pumping speed is too high, the pore water pressure in the weir body cannot be dissipated with the decrease of hydrostatic pressure. The resulting penetration will increase the risk of slope instability. Through the strength reduction method, the overall deformation of the cofferdam and the plastic development law and the minimum safety factor of the slope under different pumping speed reduction conditions are important, which is of great significance for evaluating the safety of the cofferdam.

6.1. Deformation of the slope and plastic zone
The influence of the typical reduction factor on the deformation and plasticity distribution of the cofferdam is shown in Figure 12. The position of the potential sliding surface of the slope and the shape of the sliding surface can be obtained intuitively. Under different pumping speed conditions, with the increase of the reduction factor, the shear strength of the soil material decreases, the anti-sliding resistance of the slope foot decreases, the contour of the slope foot displacement is relatively dense, and the plastic zone begins to appear from the inner slope bottom. Then, the curved plastic surface is gradually extended to the crest, and the maximum deformation is concentrated on the inner shallow slope. At the same time, local plastic deformation occurs at the foot of the outer stone slag berm, and the seepage force in the slope increases with the increase of pumping speed, which leads to the early penetration of the plastic zone of the inner weir slope and the transition of the maximum deformation to the inner slope foot, thus forming the most dangerous sliding surface. The stability of the outer weir slope is greater than that of the inner slope. If the shear strength of soil continues to be reduced, the numerical calculation is still stable, the outer slope is basically connected, and finally a double sliding surface trend is formed. However, the displacement and deformation of the slope have been seriously distorted, and the deformation has exceeded its configuration. It is not reasonable to take the convergence of numerical calculation as the criterion of slope instability.

![Figure 11. Distribution of total head and seepage slope of cofferdam](image-url)
At the end of the foundation pit drainage, the water level elevation is reduced from 63.5m to 48.5m.

### Figure 12. Cofferdam deformation and plastic zone

6.2. Safety factor and critical water level drawdown velocity of slopes

Failure of slopes can be regarded as the process of gradual development of the plastic zone, expanding into the state of complete plastic flow and unable to continue to bear the load. In order to further explore the influence of pumping speed on the safety and stability of the cofferdam slope, the feature point A, the slope foot characteristic point B displacement abruptness, and the connectivity of the slope plastic zone are used as the slope instability criterion to estimate the overall stability of the slope. As shown in Figure 13, the displacement of the characteristic point shows a similar law with the change of the reduction factor. Under different pumping speed conditions, the displacement curve decreases gently with the decrease of the reduction coefficient. After a certain time, the displacement decreases slightly. When the plastic zone of the medial slope is basically penetrated or is about to penetrate, the displacement of the characteristic point suddenly increases, and the curve drops sharply.

The reduction factor that satisfies the criterion of slope instability is the minimum safety factor, and the safety of the slope is measured. When the drawdown velocity is 0.5m/d, the seepage field and the water level fall time are more consistent. The instability of the slope is the double-slope sliding form, the stability of the slope is the best, and the safety factor $F_t$ is 1.58 (Figure 13(a)). With the increase of the speed drop, the hysteresis effect is obvious, the permeability of the inner slope is increased, and the slope stability is reduced. When the drawdown velocity is increased to 3.0m/d, the safety factor $F_t$ is at least 1.50. It is now a single-slope sliding trend, and the risk of collapse of the slope is the highest (Figure 13(f)).
The safety factor and the pumping speed reduction curve are shown in Figure 14. The cofferdam safety factor has a multi-stage linear decreasing trend. The linear descending rate varies greatly in different stages, and the turning inflection point appears at the intersection of the two straight lines. As the pumping speed decreases, the safety factor decreases sharply with the decreasing rate of the slope $k_1=0.1$. When the drawdown velocity decreases to $1.28\text{m/d}$, it decreases slowly with the decreasing rate of the slope $k_2=0.02$. Because there is a concrete anti-seepage wall in the middle of the corpus...
callosum, which blocks most of the seepage replenishment, and the inner side slope is filled with clay, the permeability is poor, and the stability of the slope is very sensitive to the change of the water level. When the pumping speed is greater than the critical speed when the speed is reduced, the height of the saturation line and the curvature of the free surface change little with the increase of the water level. The safety sensitivity of the slope is reduced, and the slope is likely to be unstable due to excessive seepage force. For soil cofferdams, the norm [12] believes that the base water level drawdown velocity is controlled within 1.5m/d, combined with the particularity of the clay cofferdam project, in order to avoid the slope of the foundation pit due to excessive osmotic pressure, resulting in slope instability causes a collapse accident, the drawdown velocity should be controlled at 1.28m/d to ensure the safety and stability of the slope during the pumping process.

7. Conclusion
Taking the temporary cofferdam project of the first phase of Yongning Water Conservancy Project as the background, considering the fluid-solid coupling theory, consider the unsaturated and seepage of clay.

Based on the conditions, the finite element method was used to accurately simulate the earth-rock cofferdam with significant adjustment of the structural form. The characteristics of the seepage field inside the cofferdam under different pumping speeds were studied. The strength of the pumping was analysed by the strength reduction method. The stability and the deformation characteristics of the key parts and the influence of the development law of plastic deformation can provide a reference for the reasonable selection of the pumping speed reduction of the temporary cofferdam foundation pit.

(1) During the pumping process of the foundation pit, the distribution of the unsaturated zone and the negative pore pressure in the crucible body are basically the same, and the total head change is mainly concentrated near the seepage prevention wall. The excessive water level slowdown easily destroys the balance between the seepage field and the water level fall time, causing the height of the saturation line and the saturation boundary line to rise synchronously and the degree of upward bending is increasing, the hysteresis effect is obvious, and the anti-seepage wall eliminates the water head and reduces the seepage. The ability to control is weakened and the problem of stable penetration is outstanding.

(2) The shear deformation of the slope begins to develop at the inner bottom of the slope, and then gradually forms a curved plastic surface to the dome. At the same time, local plastic deformation occurs at the foot of the outer gravel bank. The seepage force in the slope decreases with the pumping speed. Increased and strengthened, the plastic zone of the medial slope is penetrated in advance, and the maximum deformation transitions to the inner slope foot to form the most dangerous sliding
surface. The stability of the outer slope is greater than that of the inner slope.

(3) The safety factor of cofferdam decreases with the increase of water level drawdown velocity. When the pumping speed is greater than the critical speed, the height of the saturation line and the curvature of the free surface of the seepage change little with the increase of the water level. The safety sensitivity of cofferdam slope decreases, and the slope is likely to lose stability due to excessive seepage force. In combination with the particularity of the clay cofferdam project, in order to ensure the safety and stability of the slope during the pumping process, the drawdown velocity should be controlled within 1.28m/d.

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