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A finite element method with fluid-solid coupling to study the effect of complex water flow on the stability of reservoir dams

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Abstract In order to clarify the stability of reservoir dams under the action of rainfall, flooding and other complex water flows, this paper takes the Shifosi channel-type reservoir as the basis, and establishes a finite element numerical analysis model of fluid-solid coupling by using SLOPE/W software. The basic unknown quantities such as infiltration line position, effective plastic strain and horizontal displacement of the reservoir dam are solved sequentially by the sequential solution method to simulate the mechanical behaviors of the reservoir dam under different water flows, so as to study the stability of the dam. The study shows that with the change from normal storage to flood, the water level of the reservoir dam body is increasing, the position of the internal dip line is elevated, the maximum plastic strain and horizontal displacement of the dam body increase, and the maximum values are all found at the foot of the dam location. The FOS for the three complex working conditions were 1.931, 1.864 and 1.842, respectively. This indicates that the stability of reservoir dams is, in descending order: normal storage > rainfall > flood.

Index Terms slope/w software, finite element, fluid-structure coupling, horizontal displacement, reservoir dam, stability

I. Introduction

In water conservancy project, water is the main breaking role in its stability influencing factors, seepage problem is related to the normal operation of the project as well as its own safety and stability. With the development of industry, the dam height and reservoir capacity of reservoirs are also gradually becoming larger, and its seepage stability is more difficult to control [1], [2]. So far, in terms of geotechnical exploration, there have been many studies on the seepage stability of reservoir dams, and the relevant theories have been gradually improved, but most of them have been involved in geotextiles, and most of them are only focused on the specific effects of seepage fields, and few scholars have considered the coupling factors of stress field and seepage field to study the common impact of seepage stability of tailings dams, and simplified the interaction between field and field factors, so that there are some differences between the research results and the actual situation [3]-[6]. Therefore, it is important to explore the effect of complex water flow on the stability of reservoir dams by considering the interactions between various fields such as stress field, displacement field, and seepage field in an integrated manner [7].

With the progress of science and technology as well as the rapid development of computer technology, the numerical analysis method stands out and is favored by the majority of scholars, and the numerical analysis method contains the finite element method, the boundary element method, the variational method and the difference method and other analysis methods [8]-[10]. Among them, the finite element method is most commonly used. Jianbin, X et al. found the distribution of saturated seepage and unsaturated seepage in tailings dams as well as the distribution pattern of their stress and seepage fields in reservoir dams [11]. Xie, J. B et al. used finite element analysis software MIDAS GTS to simulate the role of factors affecting the seepage field in the steady saturated-unsaturated state of the three-dimensional seepage field of a tailings dam, and the simulation results can be in good agreement with the measured results [12]. Komasi and Beiranvand used a combination of numerical simulation and instrumental data to investigate the seepage and stability of dams, and explored the changing law of pore water pressure and slope stability during rapid descent [13]. Zedan, A. J et al. evaluated the stability and seepage characteristics of a reservoir dam under various operating conditions using finite element analysis and found that the core layer of the dam plays a significant role in reducing seepage and outlet gradients [14]. Ahmad, A et al. evaluated the stability of a reservoir rock dam using the finite element method and limit equilibrium method, which showed that the earth dam exhibited stable and reliable performance in terms of seepage flow prevention, slope collapse prevention, and resistance to dynamic loads [15]. Yang, M et al. conducted a comprehensive safety analysis study of a concrete heartwall reservoir dam with hazard control and reinforcement measures in order to analyze the seepage conditions and slope stability using a new finite element analysis method [16]. As summarized above, scholars at home and abroad have made considerable achievements in the study of reservoir dam stability by using the finite element method, and proposed numerical analysis models with practical significance [17]. However, many studies simply consider the influence of a single factor on the seepage stability of the dam body, and seldom comprehensively consider the common influence of the role of various complex flow fields on the stability of reservoir dams, which makes the relevant research can not be a good and comprehensive response to the stability of reservoir dams under the complex water flow environment [18]-[20].

Through the combination of fluid finite element and structural finite element, the coupled numerical analysis model of water flow-reservoir dam body dam is established by using finite element software, and the coupling of fluid field and solid field is carried out. Sequential solution method is used to solve the fluid calculation region and solid calculation region sequentially, so as to simulate the various mechanical behaviors of the reservoir dam body under the action of water flow. In this paper, we take a river-type reservoir on the main stream of Liaohe River as an example, and select the SEEP/W and SLOPE/W modules in GeoStudio 2007 to carry out numerical simulation. The basic unknown quantities such as the position of infiltration line, effective plastic strain and horizontal displacement of the reservoir dam body under the complex water flow environment are investigated to explore the stability of the reservoir dam body.

II. Finite element calculation method based on fluid-structure coupling

II. A. Theoretical foundations

Dam stability analysis has always been a complex research topic, the early stage is through a large number of practical engineering observation and experimentation to get a certain regular analysis method. Immediately after the subsequent production, life and related analysis and discussion, and slowly formed a number of fixed formulas and mathematical models, these analytical methods are known as the classical method. Although there are people to discuss the stability of the dam body this classic problem, but to this day has not been a good solution to this problem. Because of the limitations of the current common methods, generally when analyzing the stability of geotechnical dams, the damage analysis and deformation analysis will be analyzed and discussed separately. In the damage analysis, it is assumed that the material is an ideal rigid-plastic geotechnical body. However, in the deformation analysis, the material is often assumed to be linear-elastic. In general, dam stability analysis methods can be divided into two main categories: qualitative and quantitative analysis.

Fluid-solid coupling is an independent branch generated by the merger and cross-generation of fluid mechanics and solid mechanics, and its research object is the various behaviors of solids under the action of the flow field as well as the effect of solid deformation or motion on the flow field [21]. Its important characteristic is the interaction between the two-phase medium, the dynamic load of the solid under the action of the fluid will produce deformation or movement, solid deformation or movement, in turn, affect the flow field, thereby changing the fluid load range and value, it is this interaction will be generated under different conditions of fluid-solid coupling phenomenon. In general, the fluid-solid coupling mechanism can be divided into two categories: one is the coupling effect occurs only in the two-phase interface, the balance of the equations on the surface of the coupling is coordinated by the two-phase coupling surface on the introduction. The second is that the two phases overlap in part or in whole, it is difficult to clearly separate, so that the equations describe the physical phenomena, especially the intrinsic equations for a particular physical phenomenon is the need to establish the coupling effect, through the description of the problem of the differential equations to show.

ADINA finite element analysis software was developed in 1975, and has gradually become the most widely used finite element analysis software in the world. On the one hand, it is powerful enough to be used in a wide range of applications, such as engineering projects, education, and scientific research, and so on, where it can be of service and help. On the other hand, its source code is open code, for the later emergence of many finite element analysis software provides the basis of the code. ADI-NA software to carry out the development of its commercialization, to focus on the solution of nonlinear finite element, fluid-solid coupling, heat-mechanical coupling, etc., the program performance is reliable, high efficiency, strong analytical ability, in a global leading position. After nearly 20 years of commercial development, finite element software is widely used in various industries, including marine development, aerospace, construction engineering, highway and railroad, automobile and shipbuilding, machinery and electronics, and oil and gas energy [22].

II. B. Fluid control equations

The flow of fluids is subject to physical conservation laws. The basic conservation laws include: the law of conservation of mass, the law of conservation of momentum, and the law of conservation of energy. For a general Newtonian compressible fluid, the conservation laws can be described by the following governing equations:

Mass Conservation Equation:

$$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \tag{1}$$

where u, v, and w denote the flow rates in the transverse, longitudinal, and vertical directions, respectively, and ρ denotes the density of water.

The law of conservation of momentum can be stated as follows: the rate of change of fluid momentum in a microelementary body with respect to time is equal to the sum of all external forces on the microelementary body. The three-dimensional momentum conservation equation derived from the law of conservation of momentum is:

$$\frac{\partial(\rho u)}{\partial t}+div(\rho u\overline{u})=div(\mu gradu)-\frac{\partial p}{\partial x}+S_u \tag{2}$$

$$\frac{\partial(\rho v)}{\partial t}+div(\rho v\overline{u})=div(\mu gradv)-\frac{\partial p}{\partial x}+S_v \tag{3}$$

$$\frac{\partial(\rho w)}{\partial t}+div(\rho w\overline{u})=div(\mu gradw)-\frac{\partial p}{\partial x}+S_w \tag{4}$$

where P denotes the pressure acting on the micrometric body; μ denotes the kinetic viscosity; s_u, s_v and s_w denote the generalized source terms of the momentum conservation equations, $S_u=F_x+s_x, S_v=F_y+s_y, S_w=F_z+s_z$, F_x, F_y, F_z denotes the body force of the microelement, and since the computed fluid only considers gravity and the z axis is vertically upward, $F_x=F_y=0, F_z=-\rho g$, and the expressions for s_x, s_y and s_z are as follows:

$$s_x=\frac{\partial}{\partial x}(\mu\frac{\partial u}{\partial x})+\frac{\partial}{\partial y}(\mu\frac{\partial v}{\partial x})+\frac{\partial}{\partial z}(\mu\frac{\partial w}{\partial x})+\frac{\partial}{\partial x}(\lambda div\overline{u}) \tag{5}$$

$$s_y=\frac{\partial}{\partial r}(\mu\frac{\partial u}{\partial y})+\frac{\partial}{\partial y}(\mu\frac{\partial v}{\partial y})+\frac{\partial}{\partial \tau}(\mu\frac{\partial w}{\partial y})+\frac{\partial}{\partial y}(\lambda div\overline{u}) \tag{6}$$

$$s_z=\frac{\partial}{\partial x}(\mu\frac{\partial u}{\partial z})+\frac{\partial}{\partial y}(\mu\frac{\partial v}{\partial z})+\frac{\partial}{\partial z}(\mu\frac{\partial w}{\partial z})+\frac{\partial}{\partial z}(\lambda div\overline{u}) \tag{7}$$

In the above equation, λ denotes the second viscosity, which is generally taken as $\lambda=-2/3$; in general, the values of s_x, s_y and s_z are relatively small, and the calculated fluid is an unpressurized fluid with a constant viscosity, so that $s_x=s_y=s_z=0$.

II. C.Solid control equations

The conservation equation for the solid part is expressed under the Lagrangian description as:

$$\rho_s\ddot{d}_s=\nabla\cdot\sigma_s+f_s \tag{8}$$

where ρ_s denotes the solid density, σ_s denotes the Cauchy stress tensor, f_s denotes the volumetric force vector, and $\ddot{d}_s$ denotes the local acceleration vector in the solid domain.

II. D.Finite element discretization equations

(1) Fluid domain

The momentum equation is discretized in the spatial domain using SLOPE/W finite elements [23]. The assembled overall coefficient matrix is shown in the following equation:

$$GU=0 \tag{9}$$

$$M\dot{U}+\Lambda U+CP+K_\mu=F \tag{10}$$

where, G - continuous matrix, M - overall mass matrix, Λ - convective term matrix, K_μ - fluid viscosity matrix, C - pressure matrix, U - time derivative of pressure, velocity in ALE coordinate system, F - external load vector for the momentum equation.

Express Eqs. (9) and (10) in matrix form as:

$$M_f\dot{\Phi}_f + C_f\Phi_f = F_f \tag{11}$$

In the formula:

$$M_f = \begin{Bmatrix} 0 & \\ & M \end{Bmatrix}, C_f = \begin{Bmatrix} 0 & G \\ C & \Lambda + K_\mu \end{Bmatrix} \tag{12}$$

$$\Phi_f = \begin{Bmatrix} p \\ u \end{Bmatrix}, F_f = \begin{Bmatrix} 0 \\ F_f \end{Bmatrix} \tag{13}$$

To couple to the solid part, the unknown vector in Φ_f is decomposed into two parts:

$$\Phi_{fs} = \begin{bmatrix} P_f \\ u_f \\ \ddot{u}_{f-s} \end{bmatrix} \tag{14}$$

Other matrix forms can also be represented in chunks as:

$$M_f = \begin{pmatrix} 0 & & \\ & M_i^f & M_{ic}^f \\ & M_{ci}^f & M_c^f \end{pmatrix}, C_f = \begin{pmatrix} 0 & G_i & G_e \\ C_i & \Lambda_i + K_{i\mu} & \Lambda_{ic} + K_{ic\mu} \\ C_e & \Lambda_{ic} + K_{ic\mu} & \Lambda_c + K_{c\mu} \end{pmatrix} \tag{15}$$

$$F_f = \begin{Bmatrix} 0 \\ F_i^f \\ F_c^f \end{Bmatrix} = \begin{Bmatrix} 0 \\ F_i^f \\ 0 \end{Bmatrix} \tag{16}$$

Since the boundary of the fluid-solid coupling is a displacement boundary condition for the fluid, the right end quantity $F_c^f = 0$

(2) Discrete equations in the solid domain:

$$M_s\ddot{d} + C_s\ddot{d} + K_s d = F_s \tag{17}$$

To couple with the fluid part, the unknown vector d is decomposed into two parts:

$$\Phi_s = \begin{Bmatrix} d_s \\ d_{s-f} \end{Bmatrix} \tag{18}$$

Other matrix form chunks are represented as:

$$M_s = \begin{bmatrix} M_i^s & M_{ic}^s \\ M_{ci}^s & M_c^s \end{bmatrix}, C_s = \begin{bmatrix} C_i^s & C_{ic}^s \\ C_{ci}^s & C_c^s \end{bmatrix}, K_s = \begin{bmatrix} K_i^s & K_{ic}^s \\ K_{ci}^s & K_c^s \end{bmatrix} \tag{19}$$

$$F_s = \begin{bmatrix} F_i^s \\ F_c^s \end{bmatrix} \tag{20}$$

For solids, the fluid-solid coupling boundary is treated as a Neumann boundary condition, and F_c^s is obtained from the fluid-solid boundary condition.

II. E. Coupled flow-solid equations

Fluid-solid coupling also follows the most basic conservation principle, so at the interface of fluid-solid coupling, the conservation of variables such as fluid and solid stress (τ), displacement (d), temperature (T), heat flux (q), etc., should be satisfied, i.e., the following four equations are satisfied:

$$\begin{cases} \tau_f \cdot n_f = \tau_s \cdot n_s \\ d_f = d_s \\ T_f = T_s \\ q_f = q_s \end{cases} \tag{21}$$

The above is the basic control equations used in the computational analysis of fluid-solid coupling, in order to facilitate the analysis, the general form of the control equations can be established, and then define the value of each parameter as well as the appropriate initial boundary conditions for unified solution. Currently, the methods used to solve the fluid-solid coupling are direct coupled solution method and separation solution method. Direct-coupled solving is performed by coupling the fluid and solid control equations into the same matrix equations, i.e., solving both the fluid control equations and the solid control equations in the same solver.

$$\begin{bmatrix} A_{ff} & A_{fs} \\ A_{sf} & A_{ss} \end{bmatrix} \begin{bmatrix} \Delta X_f^k \\ \Delta X_s^k \end{bmatrix} = \begin{bmatrix} B_f \\ B_s \end{bmatrix} \tag{22}$$

where k denotes the iteration time step; A_{ff} denotes the system matrix of the flow field. The ΔX_f^k denotes the force to be solved; B_f denotes the external force. Similarly, $A_{ss}, \Delta X_s^k$ and B_s correspond to the solid domain terms, respectively. The A_{sf} and A_{fs} represent the coupling matrices of the flow and solid.

Using the direct coupled solution method to solve the control equations of fluid and solid, there is no time lag problem, so the direct coupled solution method is very advanced theoretically, but in the process of practical application, it is difficult to link the existing CSM and CFD solution techniques together, coupled with the time-consuming and convergence difficulty of the direct coupled solution, the coupling of fluid and structure can only be The coupling of fluid and structure can only be applied in some very simple studies, and it does not play an important role in engineering applications.

II. F. Limit equilibrium method

Limit equilibrium method has been developed for a long time and widely used.In 1776, the Coulomb earth pressure theory was formed by calculating the earth pressure of retaining wall, which means the beginning of the basic theory of geotechnics. In 1857, two algorithms of active earth pressure and passive earth pressure were derived by combining the semi-space stress pattern of soil and limit equilibrium conditions. Later, this method of calculating earth pressure was extended to foundation bearing capacity and dam stability, and developed into the present limit equilibrium method [24]. The basic idea is to use the mathematical method to solve the system of static equilibrium mathematical equations on the known slip surface under the limit equilibrium state of the dam body, and then solve the coefficient of safety of the dam body. However, in many cases, the system of equations cannot be solved due to the unknown boundary conditions, and it is necessary to introduce some assumptions to simplify the situation so that the system of equations can be solved. The equilibrium equation is generally calculated by the ratio of the shear force of the soil on the potential slip surface of the dam body to the shear stress on the soil under the external load, and the factor of safety of the dam body in the limit state can be obtained by calculation. The most important expression is:

$$\tau = c' + \sigma' \tan \varphi' = c' + (\sigma - u) \tan \varphi' \tag{23}$$

Where, τ - shear stress on the sliding surface, c' - the effective cohesive force, σ, σ' - total and effective normal stresses on the sliding surface, u - coefficient of friction, Φ' - effective angle of internal friction of the rock and soil.

Because of the simplicity of this method, so it is widely used in engineering, in the development of a series of methods produced by the Swedish Peterson through a number of field observations, experiments, analysis, and found that the dam in the instability of the dam formed in the destabilization of the damage to the shape of the damage surface is similar to the cylindrical surface. So he put forward the Swedish arc method of today's name.

Sweden's Ferranius on the basis of the theory of the dam body is divided into a number of vertical soil strips, these soil strips as a rigid body, to the center of the arc as a reference point, the point to solve the moment equilibrium equations, the obtained sliding moment and anti-slip moment is the coefficient of safety of the dam body. Under the continuous development of related researchers, a variety of equilibrium methods have been produced, including Bishop (Bishop) strip method, Janbu (Janbu) strip method, etc. These methods, although in the basic theory, are very simple and easy to use. Although these methods are consistent in the basic theory, the assumptions of sliding surfaces, the equilibrium conditions of forces and moments, and the assumptions of interstrip forces are different. Limit equilibrium methods have gradually evolved from empirical observations to a set of theoretical stability analysis methods. Although these methods can calculate the approximate solution of the ultimate load and the corresponding safety coefficient, they do not take into account the intrinsic relationship and some boundary conditions, and are only applicable to some simple homogeneous dams, which has a large limitation, and are not applicable to some complex dams.

III. Research on the influence of complex water flow on the stability of reservoir dams

III. A. Physical parameters of reservoir dams under complex flow conditions

The cofferdam of Shifosi Reservoir is subject to the joint action of runoff and surge, with strong hydrodynamic force and complicated water flow conditions. Shifosi Reservoir is a river type reservoir on the main stream of Liao River, the dam site is located in Huangjia Township, Xinchengzi District, Shenyang City, Liaoning Province, with a design capacity of 185 million m³, flood control capacity of 160 million m³, and a controlled watershed area of 165,000 km². 2024 July 20-21, the upstream areas of Shifosi Reservoir dam site suffered from heavy rainfall, and a number of landslides occurred in the reservoir area. Among them, Baisha landslide is located in Baisha section of the right bank of the reservoir, with a width of about 190m, an area of 50,000m² and a volume of about 800,000m³. Scouring by heavy rainfall on July 25, 2024, the landslide deformation has a tendency to further aggravate.

Shifosi Reservoir is a typical plain reservoir, and the foundation of the reservoir dam body is characterized by quaternary cover. The landslide material is mainly composed of loose accumulations of the Quaternary system, and its causes are mainly slope accumulation, artificial accumulation and flood accumulation. The landslide body can be divided into two layers according to its composition: the upper layer is mainly gravel soil and gravel-containing clay soil. The lower layer is mainly gravel soil and isolated rock mass. The groundwater in the reservoir dam body is mainly bedrock fissure water, which is mainly stored in the lower bedrock. Sampling of soil in the slip zone of the landslide body for indoor tests, the physical and mechanical parameters of the soil in different layers were obtained as shown in Table 1.

After years of research and theoretical practice, a large number of numerical simulation software on the stability of reservoir dams have been formed, and the theoretical basis and focus of these software tend to be different, so users should choose according to the actual engineering characteristics. In view of the complex water flow in this study, i.e., rainfall, flooding on the water level fluctuations and the stability of reservoir dams is a very complex process, and mainly through the change of the hydrodynamic field of the landslide body and the physical and mechanical properties of the geotechnical body and then the stability of the landslide body changes. Therefore, the first task of the simulation is to simulate the response process of landslide seepage field under different working conditions, so this paper selects the SEEP/W and SLOPE/W modules in GeoStudio2007 for simulation. The specific calculation idea is: firstly, set the calculation boundary conditions in SEEP/W module to realize the simulation of rainfall intensity and water level rise and fall, and then import the pore water pressure distribution results based on the seepage field simulation, and carry out the coupling analysis between the two, and finally realize the simulation results of the changes in the stability of the landslide.

Table 1: Shows the results of the physical mechanical parameters of the samples

Test item	Results	Test item	Results
Moisture content	10.6-19.5	Plastic limit	15.5-19.4
Natural density	1.73-2.04	Plasticity index	9.3-12.5
Natural severity	16.4-20.6	Fluid index	-0.2—-0.4
Permeability coefficient	3.6×10^{-6}-6.5×10^{-5}	Straight shear cohesion	16.6-56.8
Soil density	2.83-2.89	Straight shear Angle	11.3-40.2
porosity	0.32	Triaxial cohesion	15.9-54.2
Fluid limit	26.5-28.5	Three axis Angle	4.3-23.9

III. B. Calculation of working conditions

For the dam stability project, due to the rainfall and flooding on the water level rise and fall of the impact, the project volume is generally larger, the construction period is tighter, the environmental factors are very complex. The variation range of water flow velocity is Fr=0.036~0.237, and the variation range of water flow angle β is 0°~90° clockwise angle with the ship's longitudinal axis. The complex flow condition is the change of flow direction from 0° to 90° and from 90° to 0° along the draft depth of the dam. According to the existing data in the reservoir under the action of complex water flow each water level to take the calculation of the working conditions, each working condition is shown in Table 2.

Generally speaking, control the stability of the upstream slope of the dam for the unfavorable water level and water level plunge, water level plunge conditions from the design flood water flow and normal storage water flow plunge to the top of the spillway weir elevation of 136.0m, from the design flood level plunge to the normal storage level and from the normal storage level plunge to the dead water level conditions. On the downstream slope, to analyze the reservoir water level for the check flood level of 147.84m under the case of the dam body to form a stable seepage flow of the very application of the conditions of stability and safety of slip resistance.

During the water level plunge, the stabilizing effect of water on the upstream dam face disappears, but the pore water pressure in the dam body may still remain high, and thus the stability of the upstream face is greatly reduced.The SLOPE/W software cannot directly draw the infiltration line when the water level falls, which can be directly drawn on the model based on the past experience. In addition, the stability during water level plunge in SLOPE/W can be modeled and analyzed by two types of methods: the effective strength method and the stepwise undrained strength method. A simple and conservative effective strength method is used in this calculation, which assumes that the water level plunge occurs instantaneously and the stability-friendly water load on the upper surface of the dam body is reduced, but the water pressure within the existing body remains unchanged. Usually this method represents the most unfavorable working condition because water level plunges seldom occur instantaneously and the pore water pressure in the upstream trivial body dissipates during water level fall, so this method is more conservative.

Table 2: Operating schedule

Operating condition	Name	Water level	Bank water level
1	Flood	Check flood water	147.84
2	Rain	Design flood	143.92
3	Normal water	Normal water	141.02
4	Still water	Dead water	133.53

III. C. Effects of complex water flow changes on dam slope stability

III. C. 1) Effects of complex flow changes on the location of infiltration lines

In order to study the changes in the location of the infiltration line of the dam body under the abnormal water level such as heavy rainfall and flood, the changes in the infiltration line with the rise of the water level are plotted, and the results are shown in Figure 1. It can be seen that with the rising water level, the dam body infiltration line in the upstream slope of the dam gradually concave to the upstream, the higher the water level, the greater the amplitude, from the normal storage level up to the design flood level, the infiltration line height of 2-3 m, from the design flood level to the design flood level, the infiltration line height of less than 1 m, and infiltration line of the depth of the reservoir with the reservoir level of the water level increases and becomes smaller. The distribution pattern of the three infiltration lines from low to high reservoir water level is basically the same, and they all overflow through the middle of the downstream of the earth and rock dam.

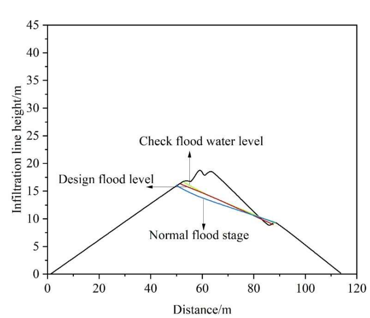
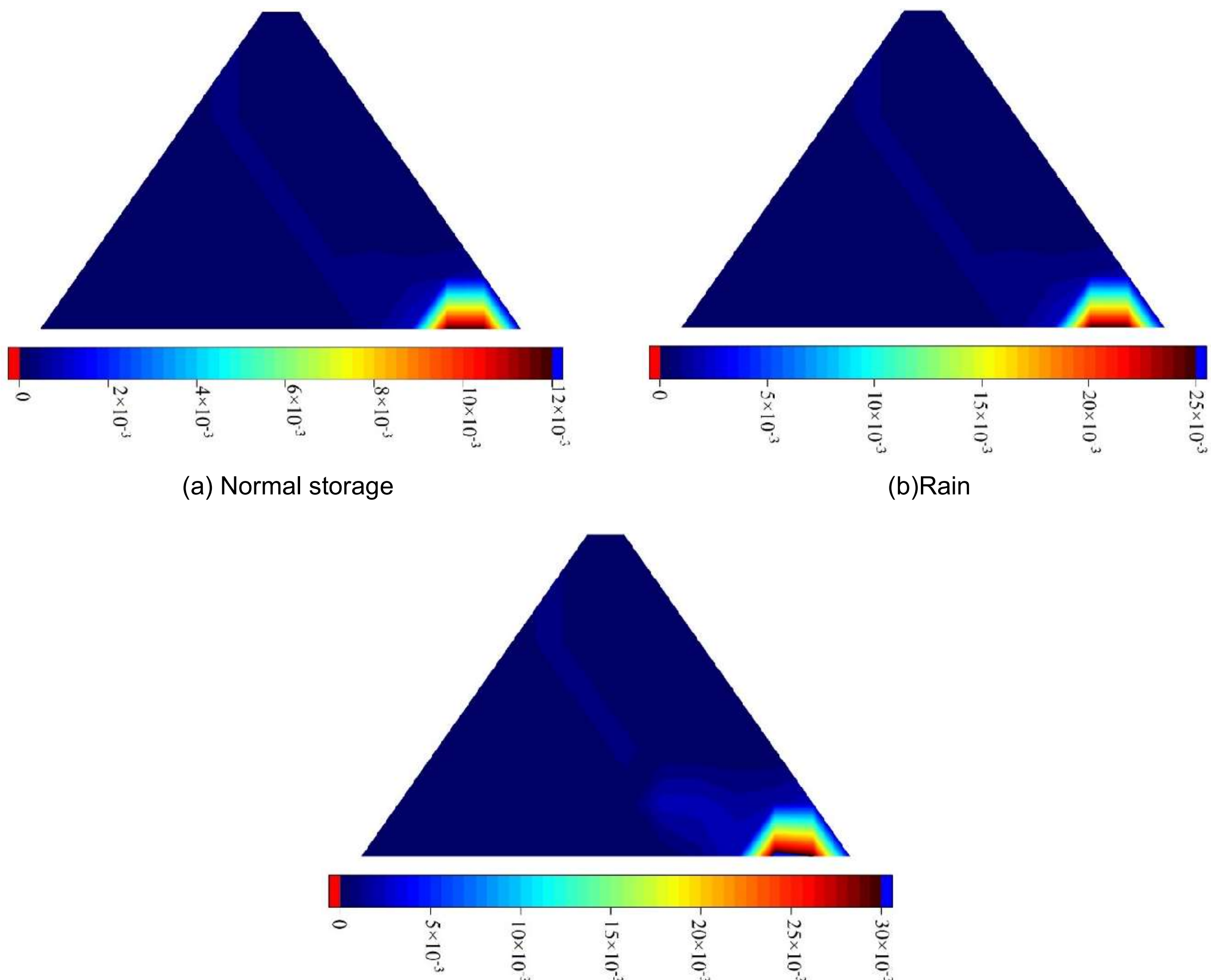


Figure 1: Dam phreatic line under three reservoir water flow

III. C. 2) Effect of complex water flow changes on effective plastic strain

The plastic zone penetrating from the foot of the slope to the top of the slope was taken as one of the criteria for critical dam failure.Based on the limit equilibrium method, the effective plastic strain and FOS were calculated for the dam slope instability at three reservoir levels as shown in Fig. 2. The maximum value of effective plastic strain is 12×10^{-3} during normal storage, and the SRF of the earth-rock dam at this time is 1.931. During rainfall, the maximum value of effective plastic strain is 25×10^{-3}, and the SRF of the earth-rock dam at this time is 1.864. The maximum value of effective plastic strain is 30×10^{-3} during flood, and the SRF of the earth-rock dam at this time is 1.842. The value of plastic strain increases continuously with the rise of the reservoir level, and the SRF of the earth-rock dam is 1.842, and the value of plastic strain increases continuously with the increase of reservoir level. The plastic strain value increases with the rise of reservoir water level, while the SRF decreases. The effective plastic strain value in the bottom of the dam foot is the largest, which indicates that the dam foot is easy to be damaged, in line with the characteristics of traction slip. 3 kinds of water flow and water level under the dam slope slip in the form of similar, the shape of the slip surface performance of the circular arc. From the principle of limit equilibrium method, the shear strength of the dam body material decreases with increasing SRF, so the plastic strain value increases, the plastic zone from the foot of the dam all the way to the top of the dam, and the dam slope will be destabilized in the interconnected shear damage surface, so the results of the FOS calculations for the three reservoir water level conditions are 1.931, 1.864 and 1.842, respectively.



(a) Normal storage (b)Rain

(c)flood

Figure 2: Equivalent plastic strain cloud map

III. C. 3) Effects of complex flow changes on horizontal displacements

The sudden change of the displacement of the internal characteristic parts of the dam body can also reflect the instability of the dam slope, and the relationship between the displacement of the characteristic parts of the dam slope and the SRF under the three types of water flow is shown in Fig. 3. In this paper, the initial SRF is set to 1.0, and it can be seen from the figure that when the SRF increases from 1.0 to 1.8, the horizontal displacements under the three types of water flow characteristics change very little, which indicates that the dam slope is in a stable state at this stage. Under normal water storage, the horizontal displacement is 27.40 mm when the SRF is 1.64, but when the SRF reaches 1.68, the horizontal displacement suddenly increases to 53.46 mm, and the numerical calculations do not converge, which means that the dam has reached the critical damage. Similarly, under rainfall and flood, the horizontal displacements of SRF at 1.64 and 1.59 are 27.40 mm and 27.37 mm for both conditions, respectively, and the FOS under normal storage is larger than that of flood, which also indicates that the increase in pore water pressure reduces the stability of the dam slope.

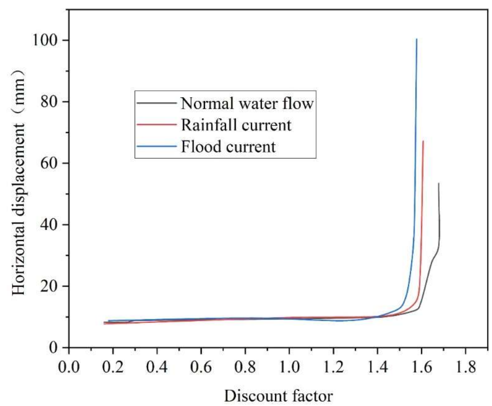


Figure 3: Horizontal displacement and fold reduction coefficient

III. C. 4) Stability analysis

Through the above theoretical analysis basis, using the plastic zone penetration and the displacement mutation of the characteristic parts as the supporting evidence, the FOS when the dam slope is unstable is obtained according to the finite element iteration solving process without convergence, and the FOS of the dam slope under different characteristic water levels is shown in Table 3. It can be seen that the FOS under three kinds of characteristic water levels are 1.931, 1.864 and 1.842, respectively, and the FOS gradually decreases when it rises from the normal storage level to the calibration flood level, indicating that with the change of water flow from normal storage to flood, the reservoir storage level rises, and the smaller the FOS is, and the stability of the dam slope gradually decreases. Among them, the maximum effective plastic strains and horizontal displacements under the three working conditions appeared at the location of the dam foot, and the shape of the slip surface showed a circular arc. Referring to the critical minimum coefficient of 1.25 required by the specification, all the three working conditions are in a safe state.

Table 3: *FO*S under different characteristic water levels

Characteristic water level	Stable safety coefficient	Maximum effective plastic strain	Maximum horizontal displacement
Check flood water	1.931	1.6×10^{-3}	49.8
Design flood	1.864	2.7×10^{-3}	62.9
Normal water	1.842	3.6×10^{-3}	100.8

IV. Conclusion

In order to study the impact of complex water flow on the stability of the reservoir dam, a river-type reservoir on the main stream of the Liaohe River was selected as the object of study, and the coupled numerical analysis model of water flow - reservoir dam dam was used to calculate the location of the infiltration line of the reservoir dam body, the effective plastic strain and horizontal displacement under different working conditions, respectively, and the results of the analysis showed that

(1) With the normal storage, precipitation to flood changes, the dam body infiltration line in the upstream slope of the dam gradually upward, the higher the water level of its reservoir, the greater the rise of the infiltration line.

(2) The FOS coefficients are 1.931, 1.864 and 1.842 for the three cases, respectively, and the stability of the dam body decreases continuously.

(3) The sudden change of the displacement of the internal characteristic part of the dam body can reflect the stability of the dam slope, when the SRF increases from 1.0 to 1.8, the horizontal displacement of the dam body of the reservoir has very little change, and it is in a stable state.

In conclusion, the finite element calculation method of fluid-solid coupling in this paper has universal applicability and practical significance.

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