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Numerical simulation of mechanical characteristics of concrete face rockfill dam under complicated geological conditions

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Abstract

In order to control the deformation of concrete face rockfill dams and improve the safety and stability of concrete face rockfill dams, this study uses the finite element analysis method, statistical analysis method, and numerical calculation to systematically study the stress and deformation characteristics of concrete face rockfill dam and its anti-seepage wall under complex geological conditions. The numerical simulation of the secondary development platform based on finite element software shows that the deformation caused by the foundation compression deformation, rheological deformation, and hydraulic coupling effect is the main cause of the large deformation of the overburden dam on the overburden layer. Among them, the foundation compression deformation is the main source of foundation deformation, and the deformation caused by rheological deformation and hydraulic coupling effect is the main source of secular deformation. Rockfill compression deformation is the main source of dam deformation, and the contribution of rheological deformation to dam deformation is greater than that caused by hydraulic coupling effect. In this study, the stress deformation and leakage characteristics of concrete face rockfill dam are analyzed, and the statistical laws of mechanical properties of concrete face rockfill dam are revealed. The sedimentation of the dam crest of most concrete rockfill dams is less than or equal to 0.40% H (H is the height of the face rockfill dam), and the sedimentation of most dams during the completion period is less than 1.0% H. After water storage, the panel deflection is close to the dam crest sedimentation value. Most of the dam's panel deflection is less than 0.40% H, of which more than half is less than 0.2% H. Large rockfill deformation is the main cause of panel tensile stress, as well cracking and crushing damage.

Keywords Rockfill dam · Numerical simulation · Hydraulic coupling effect · Statistical analysis method · Finite element analysis

Introduction

The concrete face rockfill dam refers to a rockfill dam with a rockfill body as a supporting structure and a concrete panel as an anti-seepage structure on the upstream surface of the rockfill (Cen et al, 2016). Due to its good safety, adaptability, short construction period, and low cost, the face rockfill dam is widely used in engineering (Jia and Chi 2015). The construction of concrete face rockfill dams has been in development for more than 120 years (Xu 2015), and its development has generally gone through three stages: the first stage was from the mid-nineteenth century to around 1940, as the early stage (Kong et al. 2015). The construction of rockfill is mainly based on throwing, supplemented by high-pressure water guns stamping; the second stage is from around 1940 to 1965 as a transitional stage (Zhou et al. 2016a). Due to the advancement of soil mechanics, geotechnical testing technology and rolling equipment, the core wall rockfill dam and the sloping core rockfill dam using soil anti-seepage body have developed considerably; the third stage is the development stage of reinforced concrete face rockfill dam from 1965 to the present (Zhang et al. 2015). The concrete face rockfill dam is crushed and compacted by vibrating rolling layer. The compressibility of the rockfill body is small, the anti-seepage effect of the panel is guaranteed, and the improvement of the design and construction of the panel structure makes the dam have good operating performance and economic benefits.

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Therefore, it has become the preferred dam type in feasibility research in China and many countries.

The advantages of economics and little construction limitations of concrete face rockfill dam, along with the rapid development of construction technology and mechanization, promote the rapid and large-scale development of rockfill dams. The construction of high rockfill dam has the characteristics of large engineering volume, high construction intensity, long construction period, and large influence by external factors (Peng et al. 2017). Due to the influence of construction sites and external environment, how to carefully and detailly design and implement effective construction organization and management for this large and complex project to achieve good economic results has become an increasingly important issue. However, it is difficult to make a relatively complete and systematic solution to the traditional construction organization design method. Therefore, with the help of computer technology and related system analysis theory and algorithm, the research on the construction process of the rockfill dam has become more and more practical (Zhou et al. 2016b; Wen et al. 2017).

Deformation control of dam body is the most important consideration for the construction of concrete face rockfill dam. The structural cracking and extrusion destruction of the slab, the tensile deformation of the joint, and the safety and stability of the dam are closely related to the deformation characteristics of the dam. In-depth study of the mechanical properties of face rockfill dams, especially under complex geological conditions, is the key to further advance the development of face rockfill dams. Summarizing the successful experience of the existing face rockfill dam, studying the basic laws of the mechanical properties of the face rockfill dam have important guiding significance for the high concrete face rockfill dam being built or about to be built.

Methodology

Deformation control of the dam is the most important consideration for the construction of the face rockfill dam. The structural cracking and extrusion failure of the panel, the tensile deformation of the joint, and the safety and stability of the dam are closely related to the deformation characteristics of the dam. How to effectively and reasonably evaluate and control the deformation of the dam is the most critical factor in determining the further development of the face rockfill dam. With the rapid development of dam construction technology for modern face rockfill dams, a large number of new technologies and methods have been adopted. However, the design requirements for today's face rockfill dams are also increasing. Although the study of deformation characteristics never stops, concrete face rockfill dam still has problems such as panel cracking and joint tension. The deformation evaluation and control of the face rockfill dam has not been well solved, especially for the study of the mechanical properties of the face rockfill dam under complex geological conditions, and there is still a lot of research work to do. In order to further obtain and manage the concrete rockfill dam, especially the stress and deformation characteristics of the face rockfill dam and its anti-seepage structure under complex geological conditions, the research content and technical route of this study are shown in Fig. 1:

Conditions for structural cracking of rockfill dam panels

The concrete face of the rockfill dam has a large exposed surface, and the exposed part is in direct contact with water and air. When the environment changes drastically, the influence will directly affect the panel, plus the quality unevenness inside the concrete; once the tensile stress generated by the external action exceeding the compressive strength of concrete, the panel will crack. The cracks continue to develop over time, which affects the durability and safety of the dam. A large number of practices have shown that cracks caused by changes in temperature and shrinkage deformation of the panel account for more than 80% of the total. For high dams, the length of the panel along the slope is very long. It can reach hundreds of meters without horizontal seams, and the problem of crack prevention is more prominent.

Broadly speaking, the problem of concrete cracking is the competition between the crack resistance and the destructive force of concrete. The crack resistance of the existing concrete is R, and its destructive force is P. When $R < P$, the panel will crack; when $R = P$, the concrete of the panel is at the critical point of cracking; when $R > P$, the panel will not crack.

$$R = E_p \varepsilon_p \tag{1}$$

In the equation, E_p is the elasticity modulus of concrete, and ε_p is the ultimate extension modulus of concrete.

Destructive power is simply expressed as:

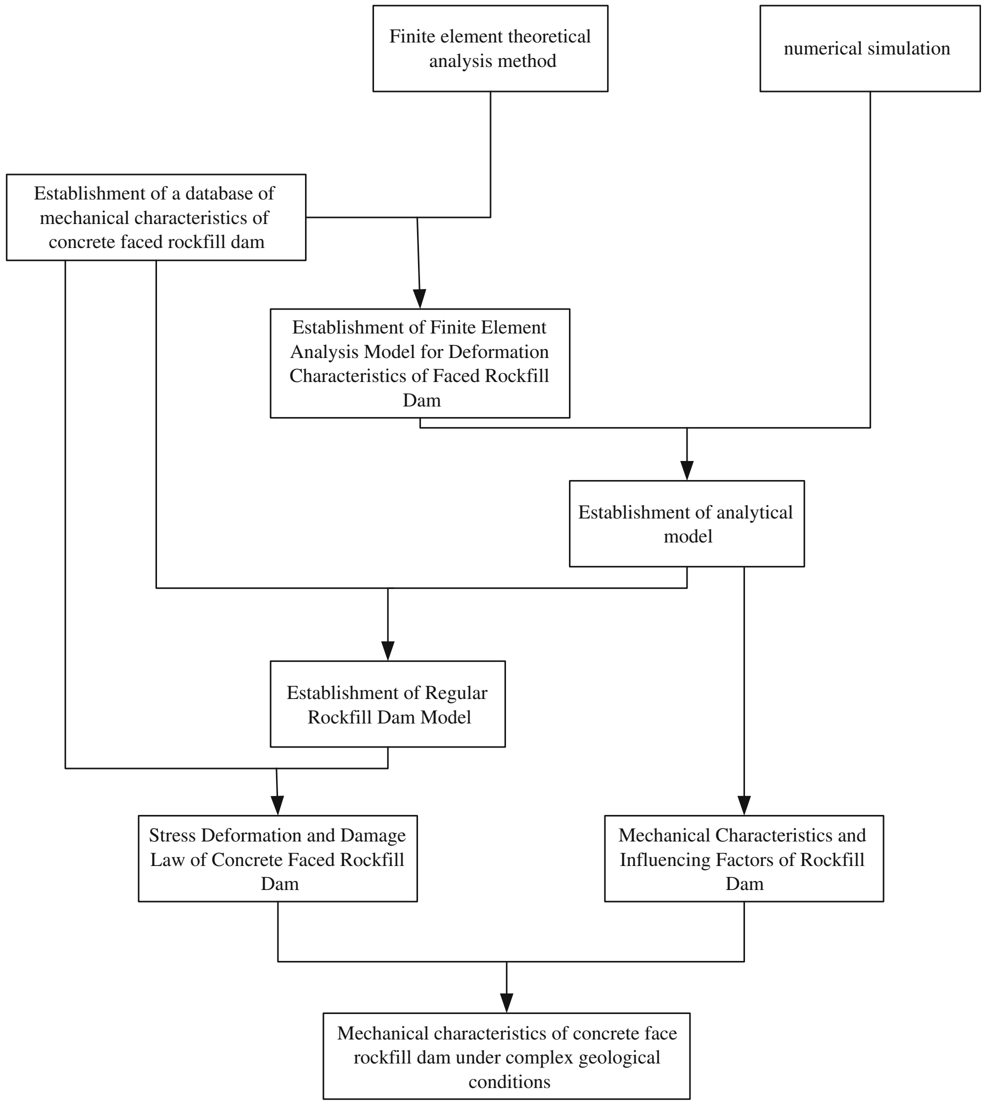
$$P = \sigma_1 + \sigma_2 \tag{2}$$

In the equation, σ_1 is the temperature stress, and σ_2 is the shrinkage stress.

The cracking conditions of panel are as follows:

$$\frac{E_p \varepsilon_p}{k} < \sigma_1 + \sigma_2 \tag{3}$$

Fig. 1 Research technical route



Dam deformation analysis and rockfill selection are closely related to the estimation of rockfill modulus. The vertical deformation modulus is defined according to the vertical sedimentation of the rockfill during the construction period, and the lateral deformation modulus is defined according to the deflection deformation of the upstream panel during the storage period. E_v and E_t are expressed as follows:

$$E_v = \gamma D H_{\mathrm{i}} / s \tag{4}$$

$$E_t = \gamma_{\mathrm{w}} \mathrm{dh}_i / \delta_s \tag{5}$$

γ represents the gravity of the rock, γ_w represents the weight of the water, and s represents the sedimentation value of the rockfill layer of thickness D when the dam is constructed to a height H_{i}. δ_s represents the deflection of the panel from the height of the water surface h_i, and d represents the height of the scalene cylinder of the dam perpendicular to the panel. E_t represents an artificially defined model and is generally only used to estimate the deflection of the panel. E_v depends on rockfill pores and rockfill strength.

Overview of finite element analysis methods

For the numerical calculation and simulation analysis of earth and rockfill dam, the actual design simulation of the dam body filling process should be considered. The earth and rockfill dam is a dam-building process in which the layered filling is carried out step by step. The calculation of each filling layer should be taken as a calculation step. This study uses the midpoint incremental method to analyze the earth and rockfill dam. One of the outstanding advantages is that the load can be applied step by step. The simulation construction adopts the method of layered loading, that is, in the first step, one layer of analysis is first loaded, and the second step is to load the upper layer on the basis of the previous layer, and so on. The initial stress of each new fill material not only affects the current loading, but also affects the stress-strain analysis of the next stage of loading. Therefore, it is important to determine the initial stress state of the rockfill.

Due to the high degree of dispersion of the rockfill body, the stress-strain relationship is very complicated. The material constants E and μ are not stable constants, but change with the stress state of the rockfill body, which means that in the finite element analysis using the model, the rockfill stiffness matrix is a function of the stress state, that is, in each incremental step, the elastic constant in the stiffness matrix depends on the magnitude of the stress in the structure of that step. It is a typical material nonlinear problem, so the equilibrium conditions and geometric relations of its elements are still consistent:

$$\{\varepsilon\} = [\mathrm{B}]\{d\}^{e} \tag{6}$$

$$\{R\}^{e} = \iint [\mathrm{B}]^{T}\{\sigma\}dxdy \tag{7}$$

In the equation, $\{\varepsilon\}$ represents unit strain column vector, $\{\mathrm{d}\}^{\mathrm{e}}$ represents unit node displacement column vector, [B] represents unit geometry matrix, $\{\mathrm{R}\}^{\mathrm{e}}$ represents unit node force vector, and $\{\sigma\}$ represents node stress column vector.

If the object of study is a linear elastic material, the stress-strain relationship of the material is consistent with Hooke's law:

$$\{\sigma\} = [\mathrm{D}]\{\varepsilon\} = [\mathrm{D}][\mathrm{B}]\{\mathrm{d}\}^{\mathrm{e}} \tag{8}$$

If the object is a nonlinear material, it is reflected in the above equation that the elastic matrix [D] changes with the stress. The stiffness matrix [K] derived based on [D] is also changed with stress, and its equilibrium equation can be briefly described by the following equation:

$$[\mathrm{K}(\sigma)]\{\delta\} = \{\mathrm{R}\} \tag{9}$$

The basic method for solving nonlinear problems in numerical calculation is the incremental method. In order to solve the calculation accuracy problem of nonlinear problems in numerical calculation, it is necessary to control the magnitude of the increment to make the calculation result of each step approximate the real solution. The so-called increment is the load increment or the time increment, and the incremental division is sufficiently fine, so the ideal calculation result can often be obtained. In the application of the face rockfill dam technology, considering the incremental method is quite consistent and adaptable to the load-bearing characteristics of the rockfill body during the construction period and the operation period of the rockfill dam, generally, the incremental method is used to solve the nonlinear problem of rockfill in the numerical calculation.

Results and discussion

Three-dimensional finite element analysis model of regular concrete face rockfill dam

The material division of the dam body is divided into the upstream face as a concrete panel, and the lower part of the panel is a contact layer, a cushion layer, a transition layer, and a rockfill body. ANSYS, a large-scale finite element software, is used to simulate the surface contact between the panel and the cushion, and a three-dimensional finite element model of the regular dam is established. The model coordinate system is defined as the upstream direction is the X-axis forward direction, the elevation direction is the Y-axis forward direction, and the left bank to the right bank is the Z-axis forward direction. The model diagram is shown below. The load application method simulates the construction filling and water storage process of the concrete face rockfill dam by means of stepwise application. The load mainly considers the self-weight load and the water load. The whole load is divided into 36-stage loading, in which the first 29 level load is filled with the dam body, the 30th level load is placed with the concrete panel, and the last 5 level load is used to apply the water load, respectively 50 m, 100 m, 150 m, 200 m, and 250 m. The midpoint increment method is used for each level of load calculation (Fig. 2).

For static calculation, the concrete panel unit adopts a linear elastic model. The elastic modulus E is 27,000 MPa, the unit weight y is 25 kN/m^3, and the Poisson's ratio u is 0.16. The Duncan E-B constitutive model is used for the rockfill body. The parameters used are shown in Table 1. The dynamic calculation rockfill uses an equivalent linear viscoelastic model. The maximum shear modulus parameter values are the

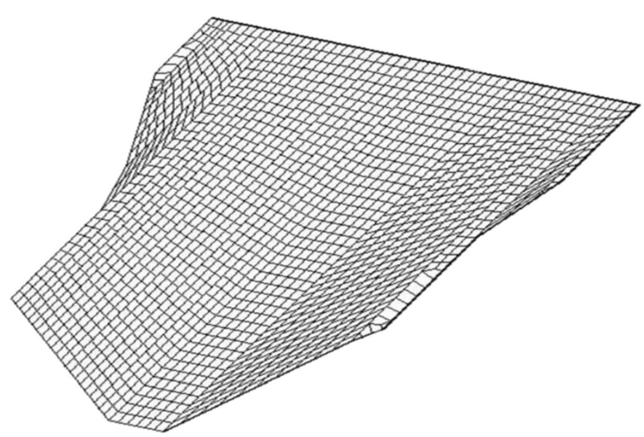


Fig. 2 Finite element model of concrete faced rockfill dam

Table 1 E-B model parameters

Material	ρ (g/cm^3)	K	n	R_f	C	φ	$\Delta\varphi$	K_b	m	K_{ur}
Contact layer	2.67	5000	0.66	0.85	0	37.8	0	400	0.5	9600
Cushion layer	2.1	1245	0.43	0.68	0	51.3	4.5	578	0.43	2365
Transition layer	2.1	932	0.38	0.77	0	50.4	4.4	463	0.41	2100
Rockfill	2.47	912	0.29	0.72	0	52.2	6.8	421	0.32	1984

average value according to multiple dam type dynamic models, and the parameters of this study are shown in Table 2 with reference to the relevant concrete face rockfill dam.

Description of mechanical properties of concrete face rockfill dam

Because the lower reservoir is not high, the bank is also gentle, and the dam axial deformation of the panel is small, which is mainly the flexural deformation. The calculation results show that the maximum deflection of the panel is 4.1 cm, the position that is higher than maximum fracture surface of the panel by the half dam height is close to the position with the combined force of the water pressure, and the deflection of the panel gradually decreases from the maximum to the periphery. There is a good correlation between the deformation distribution of the panel and the deformation distribution after the water storage on the upstream dam slope, indicating that the deformation of the concrete face mainly depends on the deformation of the rockfill body.

The stress along the slope of the panel is mainly represented by compressive stress, which appears in the middle and lower part of the middle dam panel. This is because the self-weight and water pressure of the panel are the main factors that produce the compressive stress along the slope. The panel has a small tensile stress in the range of about 1–2 m below the top surface. This is because, under the action of water pressure, the rockfill has downward and downstream displacement. Due to the Poisson's ratio effect of the rockfill, lateral deformation in the direction of water pressure will be produced. The foundation limits its lateral deformation, and the displacement synthesis result of the rockfill will be above the normal direction of the panel. This deformation trend will cause the upward shear stress of the rockfill material relative to the panel, and the panel will produce a tensile stress along the slope.

Table 2 Calculating parameters of dynamic model

Material	K	n
Cushion layer	2694.3	0.6
Transition material	2843.9	0.6
Rockfill	2731.3	0.6

The panel is mainly pressed under the direction of the dam axis, and there is a small tensile stress in the local area below the top of the panel and on the left and right banks. The compressive stress mainly comes from the self-weight and lateral extrusion trend under the action of water pressure. The tensile stress mainly comes from the rockfill body and the deformation of the panel on both sides.

The results of stress deformation of the concrete face show that the stress deformation state of the panel is better; the panel mainly bears compressive stress, occasional alternation of tension, and compression. The tensile stress only occurs in the local area, and the stress value is not large.

Conclusion

In this study, based on the characteristics of concrete face rockfill dam under complex terrain conditions, a combination of qualitative analysis and quantitative analysis, combination of process simulation and feature statistics, simulation calculation, and graphic display are used, research of concrete faced rockfill dam was carried out to establish a dynamic simulation model. Based on the E-B model, the finite element stress, and deformation analysis of the concrete face rockfill dam, including the stress and deformation distribution of the rockfill under the gravity field of the rockfill dam, it can be seen that the maximum sedimentation of the rockfill occurs near the axis of the dam body at the 1/2 elevation position, the whole rockfill body upstream of the dam body tends to shift upstream, and the downstream rockfill of the dam body tends to deform downstream. The maximum deformation of the upstream and downstream both occur on the surface of the rockfill with a displacement of about 1/2 elevation position. After the reservoir is filled, under the action of water pressure, the maximum sedimentation is offset to the upstream side of the dam, the deformation of the upstream rockfill body decreases along the river, the deformation of the downstream rockfill body along the river generally increases, and the overall stress of the rockfill body also increases. According to the calculation results, it can be seen that the tensile stress is generally acceptable except for the individual boundary areas on both sides of and near the slab where the tension is stronger, and the overall tensile stress is almost no threat to the crack resistance of the panel.

Certainly, there are still many technical problems in the research of concrete face rockfill dam under complex geological conditions. With the further development of computer technology, the realistic effect of concrete face rockfill dam and the combination of simulation technology and artificial intelligence technology have yet to be further studied to further enrich and develop simulation models and their manifestations to better serve the concrete face rockfill dam.

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