ANSYS-Based Software Development and Application of Seismic Dynamic Response Finite Element Calculation Platform for Earth-Rockfill Dams

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Abstract: Earthquake is an important factor affecting the operation safety of earth-rockfill dams. At present, the numerical calculation of earthquake conditions of earth-rockfill dams is still based on mature finite element commercial software, which is inconvenient in research, learning and practical application. Accordingly, this paper introduces the finite element calculation platform of earth-rockfill dam seismic dynamic based on ANSYS. The platform is written in Fortran language, with good user interaction and visual UI interface. The actual engineering example test shows that the results are in line with the general dynamic displacement and deformation laws of the engineering level earth-rockfill dam under seismic conditions, which verifies the accuracy of the calculation results of the platform, and has a certain promotion value.

1 INTRODUCTION

In the past 40 years, China's earth-rockfill dam engineering has made rapid progress and is developing towards ultra-high earth-rockfill dams and complex natural conditions (Zhou et al., 2019). However, observation and research on some completed earth-rockfill dams both domestically and internationally have shown that earth-rockfill dams often experience problems such as soil sliding, cracking, and leakage after earthquake action (Ye, 2022; Chen, 2009), which poses hidden dangers to the long-term operation safety of earth-rockfill dams. Therefore, how to accurately calculate the dynamic displacement and stress distribution of the dam body under earthquake response has gradually become a hot research topic in the seismic design of earth-rockfill dams.

At present, the quasi-static method and time-history analysis method are mainly used to calculate the seismic dynamic response of earth-rockfill dams. Because the quasi-static method does not consider the influence of factors such as ground motion spectrum characteristics and duration, it is not suitable to guide the seismic design of high earth-rockfill dams in a strict sense. The factors considered by time-history analysis method are more comprehensive, but there is no consensus on dynamic parameters, seismic wave input mode and other aspects in the actual calculation, which has a great impact on the calculation results (Niu, 2017). In addition, the calculation process still relies on a mature commercial finite element platform, which has problems such as high learning cost and complex modeling in practical application (Guan et al., 2023).

In this regard, a finite element calculation platform for seismic dynamic response of earth-rockfill dams is developed based on ANSYS. The platform is written in Fortran language, and the efficiency is improved by using parametric modeling and analysis method through secondary development technology. In the calculation, a variety of strength and constitutive models can be selected to realize the control of multi condition and multi task calculation process. The platform uses a preprocessing conjugate gradient solver independently developed, which is significantly more efficient than most popular solvers, and can solve the problem of tens of millions of degrees of freedom on a microcomputer; At the same time, it has a relatively perfect pre-

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processing and post-processing and visual interface, and can easily output displacement, stress and stress level contour map, liquefaction index, failure mode map, deformation contour map, etc. through menu operation, which is convenient for the analysis and collation of results, and the user experience is good.

2 GENERAL IDEA AND TECHNICAL ROUTE OF SOFTWARE

The software is developed based on ANSYS mechanical APDL platform, and its main functions include parametric modeling of earth-rockfill dam, pre-processing of finite element model, seismic dynamic calculation and post-processing of results. For seismic dynamic analysis, quasi-static method and seismic wave time-history analysis method can be used to study the permanent settlement of earthquake. The realization ideas of each function are as follows:

2.1 Parametric Modeling Module of Earth-Rockfill Dam

The platform has developed data interfaces with commercial finite element software such as ABAQUS, ANSYS, FLAC3D, etc. to facilitate the import and conversion of external model data. At the same time, the platform developed relatively convenient parametric modeling functions for homogeneous dam, concrete face dam, clay core dam and asphalt core dam.

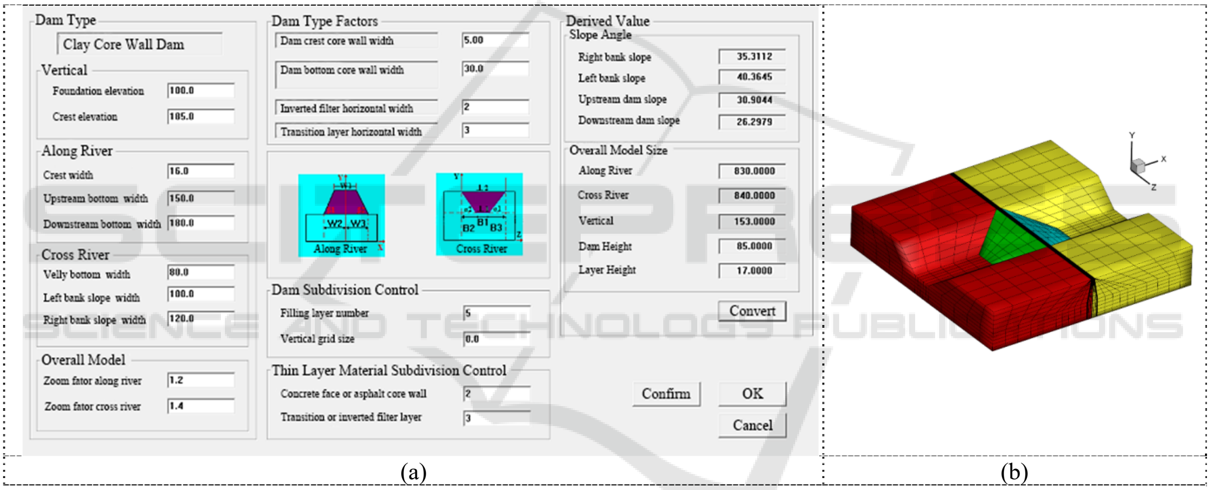


Figure 1: Parametric modeling interface and grid model.

As shown in Figure 1(a), user can set control parameters such as earth-rockfill dam type, model scale, upstream and downstream slope and bottom width in the visual UI interface, and click "OK" to quickly generate the finite element calculation grid file for this platform. After the model is generated, user can call Tecplot to open the export file to check the calculation grid model of earth-rockfill dam in Figure 1(b).

2.2 Model Preprocessing and Calculation Process Setting

After importing the earth-rockfill dam calculation grid model, user can carry out various preparations for calculation in the UI interface of the "model preprocessing" module. For seismic dynamic calculation, it mainly includes material parameter setting, seismic wave input and calculation process setting, etc.

The material parameters and seismic wave acceleration for dynamic calculation are imported into the platform from the prepared parameter sample table. User can zoom and output the seismic wave acceleration in the UI interface.

Figure 2(a) and (b) show the definition interface of parameters related to quasi-static method and seismic wave input time history method for seismic dynamic calculation of earth-rockfill dams, where users can select dynamic calculation methods and set parameters. After setting, click "OK" to start running the calculation program.

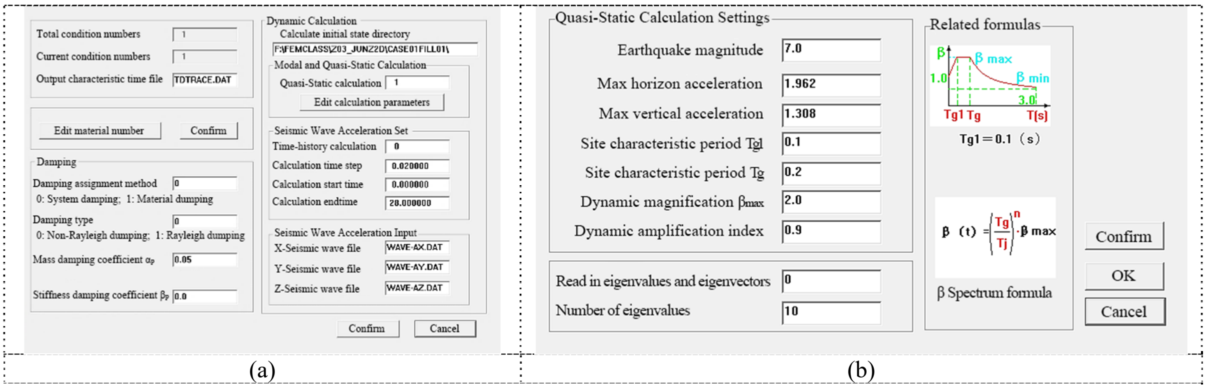


Figure 2: Preprocessing settings for dynamic calculation of earth-rockfill dams.

2.3 Theory and Method for Seismic Dynamic Calculation and Analysis of Earth-Rockfill Dams

2.3.1 Constitutive Model for Dynamic Calculation

In order to simulate the dynamic characteristics of soil and stone, an equivalent linear model is used. In the equivalent linear model, the soil is regarded as a viscoelastic body, and the two parameters of equivalent elastic modulus and equivalent damping ratio are used to reflect the nonlinear and hysteretic characteristics of the dynamic stress-strain relationship of soil, and the elastic modulus and damping ratio are expressed as functions of dynamic strain amplitude. At the same time, the influence of the average principal stress of static consolidation is considered in determining the above relationship, and the specific expression is:

$$G_{\mathrm{d}} = \frac{G_{\max}}{1+\gamma_d/\gamma_r} \tag{1}$$

$$\lambda = \frac{\lambda_{\max}\gamma_d}{\gamma_r(1+\gamma_d/\gamma_r)} \tag{2}$$

$G_{\max}$ is initial maximum shear modulus, G_{d} is dynamic shear modulus, γ_d is dynamic shear strain, γ_r is maximum equivalent damping ratio, generally determined by empirical formula.

The maximum shear modulus of soil can be expressed as:

$$G_{\max} = k_1 P_a \left(\frac{\sigma_0}{P_a}\right)^{n_1} \tag{3}$$

σ_0 is initial average consolidation stress, k_1 and n_1 are test constant, related to soil type and bulk density. P_a is atmospheric pressure.

The maximum shear stress of soil under dynamic conditions is:

$$\tau_{\max} = \lambda_1\left[\left(\frac{1+K_0}{2}\sigma_0\sin\varphi + c\cos\varphi\right)^2 - \left(\frac{1+K_0}{2}\sigma_0\right)^2\right]^{1/2} \tag{4}$$

λ_1 is dynamic correction factor, K_0 is coefficient of static lateral pressure of soil, K_0=1-sinφ . c and φ are cohesion and internal friction angle of soil.

2.3.2 Establishment and Solution of Dynamic Equation

Only under the action of seismic force, the relative motion equation of the whole system of earth-rockfill dam and overburden can be discretized into the following matrix equation form:

$$M\{\ddot{u}\} + C\{\dot{u}\} + K\{u\} = -M\{\ddot{u}_g\} \tag{5}$$

$\{\ddot{u}\}$, $\{\dot{u}\}$ and $\{u\}$ are the acceleration vector, velocity vector and displacement vector of the system. M , C and K are the respectively the mass matrix, damping matrix and stiffness matrix of the system. $\{\ddot{u}_g\}$ is the input seismic acceleration.

Assuming that the system obeys the Rayleigh damping relationship, the damping matrix can be expressed as a linear combination of mass matrix and stiffness matrix:

$$C = \alpha M + \beta K \tag{6}$$

α and β are Rayleigh damping coefficient, α=$\lambda\omega_1$, β=λ/ω_1 . ω_1 is the first order natural circular frequency.

The vibration mode superposition method and direct integration method are often used to solve the above dynamic equations. Due to the strong nonlinear characteristics of soil, the platform solver uses Newmark integral method to solve.

2.3.3 Analysis Method of Seismic Residual Deformation

The softening modulus method is used to calculate the permanent deformation of the dam body. Its basic concept is that the seismic action reduces the modulus of soil mass, resulting in residual deformation. It is assumed that the stress-strain relationship of the soil after the earthquake still conforms to the Duncan Chang hyperbolic relationship, and the stress state of the soil element before and after the earthquake remains unchanged, but the strain increases the seismic residual strain on the basis of the original initial strain, which can be deduced from the stress coordination condition:

$$E_i \varepsilon_i = E_{ip}(\varepsilon_i + \varepsilon_p) \tag{7}$$

E_i is elastic modulus of soil before earthquake, E_{ip} is elastic modulus of soil after earthquake.

Further considering the factors such as short duration of earthquake and undrained soil, the Poisson's ratio of soil after earthquake can be obtained as follows:

$$\mu_{ip} = \frac{1}{2}\left[1-(1-2\mu_i)E_{ip}/\varepsilon_i\right] \tag{8}$$

According to the static balance equation, the seismic permanent deformation of the dam is the difference between the deformation before and after the earthquake, that is, the residual permanent deformation of the dam is:

$$u_p = u_{ip} - u_i \tag{9}$$

3 CALCULATION VERIFICATION AND ENGINEERING APPLICATION

3.1 Project Overview

The maximum dam height of a core rockfill dam is 83.0m, the upstream dam slope ratio is 1:2.0, and the downstream average dam slope ratio is 1:1.8. The lowest foundation elevation of the core wall is 3121.50m, the dam crest elevation is 3204.5m, the width is 12.50m, and the axial length of the dam is about 230m. According to the seismic risk analysis report of the dam site area, the peak horizontal acceleration of bedrock with a 100-year probability of exceeding 2% is taken as 2.44m/s^2, the peak vertical seismic acceleration is taken as 2/3 of the horizontal direction, and the calculation time step is taken as 0.02s. The finite element calculation model is shown in Figure 3.

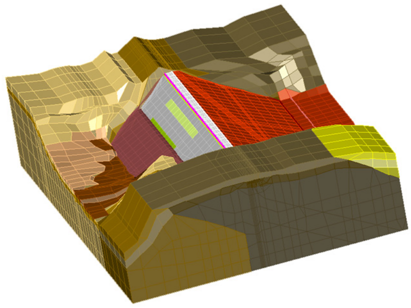


Figure 3: Finite element model.

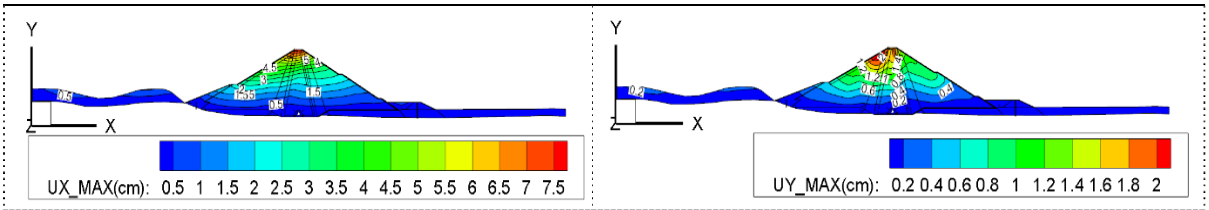
In this calculation, the time-history analysis method of input seismic wave is used to study the maximum dynamic displacement, maximum dynamic acceleration and dynamic shear stress distribution of the dam along the river and in the vertical direction under the action of ground motion load.

3.2 Seismic Dynamic Calculation Results

According to the Figure 4, the dynamic displacement of the dam body increases with the distance to the dam foundation, reaching the maximum at the top of the dam. The maximum displacement of the dam body along the river is 7.5cm, which occurs in the center of the dam crest of the riverbed profile. The maximum vertical dynamic displacement is about 2.0cm, which occurs in the upstream dam slope area near the dam crest.

In addition, Figure 5 shows that the dam body has obvious acceleration amplification effect during the earthquake. The maximum response acceleration of the dam body gradually increases with the increase of elevation, and gradually increases from the inside of the dam body to the upstream and downstream surfaces. The acceleration reaches the peak at the top of the dam.

Figure 6 shows that the maximum dynamic shear stress is 0.1~1.2MPa. There is a certain concentration of dynamic shear stress in the corridor at the bottom of the core wall, and the extreme value is about 1.2MPa, which occurs at the top of the corridor.



(a) UX (b) UY

Figure 4: Maximum seismic response dynamic displacement.

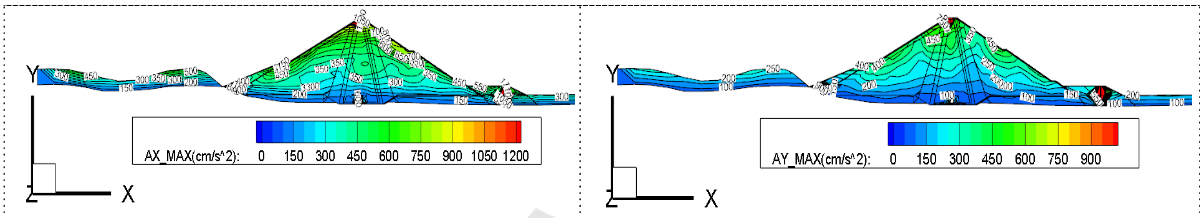


Figure 5: Maximum seismic response dynamic acceleration.

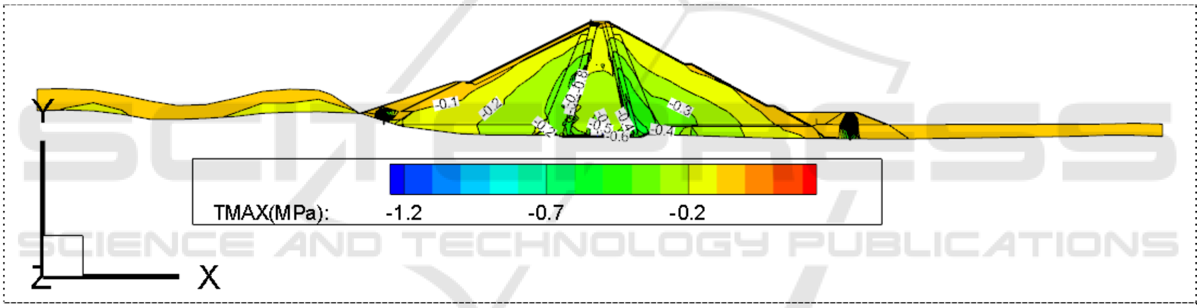


Figure 6: Maximum seismic response dynamic shear stress.

Based on the above results, it can be seen that the core rockfill dam of the project meets the seismic requirements on the whole under the action of earthquake, and the design of the core rockfill dam is reasonable, and no problems of incongruous deformation and excessive extreme deformation are found, indicating that the core rockfill dam has good seismic performance. The maximum response dynamic displacement and dynamic shear stress distribution of the dam body in the calculation results conform to the seismic response distribution law of the core wall dam of this engineering level, which indicates that the seismic dynamic calculation of the actual earth-rockfill dam project by this platform is feasible and reliable.

4 CONCLUSION

This paper introduces the main functions and technical route of the finite element calculation platform for seismic dynamic response of earth-rockfill dam based on ANSYS, as well as its application in the seismic dynamic response calculation of a core rockfill dam project. and the mainly conclusions are as follows:

(1) The finite element calculation platform of earth-rockfill dam seismic dynamic response based on ANSYS has convenient function modules and user-friendly visual interface. Compared with the commercial finite element software platform, it can greatly simplify the process and improve the calculation efficiency.

(2) The seismic dynamic calculation test of a domestic core rockfill dam project is carried out, and the calculation results accord with the seismic response distribution law of the project level core dam, which verifies the reliability and accuracy of the calculation results of the software platform, and has certain popularization value.

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