Dynamic Stability Analysis of Arch Dam Abutment Based on Strength Reduction Method

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Abstract. Dynamic stability analysis of dam abutment is related to safety, reliability and rationality, which gives significant consideration on arch dam development. This paper aims at an engineering project, using static and dynamic combined method, firstly to solve the static forces from dam body to dam abutment; Then using strength reduction method combined with seismic load from response spectrum with the same strength reduction factor to get the dynamic safety factor. The results provide design basis for the projects.

1 Introduction
Arch dam is a sort of space shell structure which is added by a number of horizontal arches in the vertical plane with complicated shape and grand scale. Both ends of arch dam are embedded in rock mass. When load as water pressure is applied to the dam, a part of the load is passed to the rock mass on both sides of the river as horizontal thrust through the arch action; the rest of the load is passed to the bedrock of the dam. Arch dam stability is mainly dependent on the rock mass of dam abutment, so local geological defect of dam abutment is likely to cause dam failure.

This paper is mainly about arch dam abutment stability and damage development process through dynamic stability analysis depended on simulation of arch dam, cushion, the main faults and other geological conditions. This paper research on deformation law and failure mechanism of arch dam under seismic load and the normal water level through strength reduction method combined with seismic load from response spectrum, get evaluation of dam abutment stabilization under seismic loading.

2 Theoretical analysis methods

2.1. Static and dynamic combined method
Gravity, hydrostatic pressure, silt pressure, temperature load should be applied to the dam body in the dynamic analysis of dam reservoir water - foundation system firstly. Earthquake load and hydrodynamic pressure are applied under seismic condition. It is a nonlinear process when the transverse joint open, closed or sliding for dynamic analysis of high arch dam. Because the analysis should consider material nonlinearity and geometric nonlinearity at the same time, the principle of superposition is no longer appropriate. Static condition and dynamic condition are calculated separately in this paper.

The static analysis is mainly about static response calculated under gravity, hydrostatic pressure, the pressure of sedimentation and the temperature load by mixed finite element method for contact...
problem.
  The displacement and stress calculated in the static analysis are used as the initial displacement and stress in the dynamic analysis. Static load except temperature load and the contact force between the seams should be considered for the balance between static internal force and static force.

2.2 Strength reduction method
The load remains the same but the shear strength decreases gradually with loading process in the calculation using strength reduction method. The location of slip surface is determined by the distribution of plastic zone and the displacement curve of feature points under different reduction factors. When displacements of finite element mesh node have a mutation, the reciprocal of reduction factor is the safety factor.

2.3 Determination of the slip surface and failure criteria
Based on the strength reduction method, the reduction factor is the reciprocal of the safety factor at the failure time. The maximum place of plastic strain can be considered as the critical slip surface. The displacement and the plastic strain is no longer a fixed value but a state of infinite plastic flow by isotropic Mohr-Coulomb standards or Drucker-Prager standards at the break time. The calculation is misconvergence after mutation in the finite element analysis. Whether the calculation is convergence or the plastic zone become to a sliding surface can be used as a failure criterion.

2.4 Response spectrum method
The vibration characteristics of the dam are gotten by considering the interaction of dam, water and foundation. The dynamic arch thrust and seismic inertia force for the overall stability dynamic analysis of dam by the response spectrum method. Based on the acting force calculated by finite element method and the safety coefficient calculated by strength reduction method, the seismic loading calculated by the response spectrum method is applied to the dam with keeping the same reduction coefficient.

3 The engineering example
Arch dam, cushion, main fault, fault zone and parting are simulated by the response spectrum method in this paper, thus stability of dam abutment under seismic load condition can be evaluated.

3.1 The finite element model
The hard-core of this paper is the safety degree evaluation of arch dam abutment stability. The whole finite element model is the most important part as a basis of the overall numerical calculation. Pairs of contact points are arranged at transverse joint to simulate opening, closing and slipping of the transverse joint. Pairs of contact points are arranged between the sliding block and the arch dam abutment to simulate the interaction under the static and dynamic loads. The water body is divided to elements in dynamic analysis. Dynamic interaction is simulated by interface elements on the interface. Truncated boundaries between upstream and downstream are treated as impermeable boundary. This paper focuses on three typical sliding blocks on the left and right bank and simulates mechanical behavior of the slip surface.

Modeling coordinates: Axial direction of the dam is X-axial. Flow direction of the dam is Y-axial. Vertical direction is Z-axial. Hexahedral isoparametric elements are used in the calculation. There are 28006 nodes and 24854 units in the whole finite element model. Finite element model and finite nodes are showed in Fig.1, 2.
3.2 The computational loads
The computational loads include hydraulic pressure and silt pressure both upstream and downstream. Hydrostatic load is calculated under normal pool level. The osmotic pressure is calculated by the method of standard. Curtain grouting and drainage facility of dam foundation are simulated considering the difference of different stratum in order to solve the seepage field and seepage pressure which are applied to finite element nodes in stress field-seepage field coupling calculation.

3.3 Physical and mechanical property parameter of the dam body
Concrete: \( \gamma_c \) (volume-weight)=24kN/m, \( E_c \) (elasticity modulus) =24GPa, \( \nu_c \) (Poisson's ratio) =0.17, \( \alpha_c \) (coefficient of linear expansion) =1.0×10^{-5}/℃.

4 Degree of dam abutment safety
Firstly, acting forces of possible slip masses are calculated by finite element internal force method. Then the forces are applied to slip masses. Earthquake load calculated by response spectrum method is applied to slip masses based on monolithic stability calculation which maintains the same material reduction factor of statical analysis. Finally strength reduction stability is analyzed with these loads.

The dam model has wide river valley and relatively low stiffness. Natural frequency of vibration is relatively low too. Vibration modes of front five steps under normal top water level which increase 50 times are showed as are showed in Fig.3.

(a)1.15Hz  (b)1.33Hz  (c)1.92Hz  (d)2.39Hz  (e)2.62Hz

Figure 3 Vibration modes of front five steps

Crack is prepared along the heavy curtain. Sliding blocks of left bank are showed in Figure3 (a) and structural surfaces are showed in Fig.3 (b). Feature points are showed in Figure3 (c). Sliding block 1, 2, 3 are analyzed by feature point A, B, C. Safety factor is reciprocal of the strength reduction factor when displacement of grid nodes is break. Safety factors of sliding blocks are showed in Fig.4.
5 Conclusions

As mentioned, displacement of feature point A is breaking when reduction factor is 0.38, so corresponding safety factor of sliding block 1 is 2.63. Displacement of feature point B is breaking when reduction factor is 0.52, so corresponding safety factor of sliding block 2 is 1.92. Displacement of feature point C is breaking when reduction factor is 0.43, so corresponding safety factor of sliding block 3 is 2.33. All safety factors are greater than 1.31 and meet requirement. Safety factor of sliding block 2 is the smallest one of three blocks, because arch thrust increases at this elevation. There will be obvious diastrophism at intersecting place of LS331 and LS3318 under gravity and arch thrust. Stability analysis of arch dam abutment by strength reduction method is proved in this paper.

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