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# The Dynamic Stability Analysis of Shapai Arch Dam Affected by Wenchuan Earthquake

**X N Li* and R Shi**

State Key Laboratory of Eco-hydraulics in Northwest Arid Region of China, Xi'an University of Technology, Xi'an 710048, China

* corresponding author

**Abstract:** The sliding wedge method and the finite element rigid body limit equilibrium method are combined to analyze the dynamic stability of shapai arch dam affected by wenchuan earthquake, and compared with the pseudo-static method. Analysis indicates that the result got by the sliding wedge method and the finite element rigid body limit equilibrium method is slightly higher than the pseudo-static method of safety coefficient. Because the changes in the size and direction of the arch abutment thrust are taken into account in the sliding wedge method and the finite element rigid body limit equilibrium method, and coincidence coefficient is considered during applying seismic inertia force. So the method referred by this paper can reflect the aseismatic working state of the arch dam. Therefore, it provides a novel means of evaluating aseismatic safety.

## 1. Introduction

The most critical issue in the study of the aseismatic safety of arch dams is the stability of dam abutment. Dam abutment rock stability can be analyzed with overloading, strength-reducing, and synthesis methods, all of which are frequently used[1]. In the overloading method, the commonly used approaches are water overloading and seismic peak acceleration. Many scholars have conducted numerical simulations and model tests on various arch dams through this method[2-3]. However, the overloading effect, which is inherent in the dam structure, is inconsistent with the actual state[4]. For example, the actual anti-slip strength of rock mass discontinuity in dam abutment is likely to be lower than the design value. In comparison, the strength-reducing method approximates reality. Chen et al.[4] proposed the concept of inflection point, where deformations are caused by absolute displacement in key parts of an arch dam system or residual displacement on sliding surfaces. The overloading or strength-reducing factor that corresponds to this point is the stability factor of dam abutment. In the process of obtaining the safety factor, if the point of contact is in a state of destruction, then the entire interface is in the ultimate limit state. This interface obeys Mohr–Coulomb theory, that is, the unstable sliding surface of dam abutment and the foundation surface evaluated by the aseismatic weak position. This approach has become valuable in the analysis of abutment aseismatic stability. However, the inflection point is difficult to determine.

In this paper, the sliding wedge method and the finite element rigid body limit equilibrium method is combined to analyze the dynamic stability of shapai arch dam affected by wenchuan earthquake.

## 2. The sliding wedge method

Wedge failure is a common destruction form in the abutment rock mass. Usually, the steep sliding surface is regarded as side sliding surface, and the slow sliding surface is often regarded as bottom sliding surface. The typical loading of wedge body is in Fig.1. The rigid body limit equilibrium method is used to solve the Wedge stability safety factor in the limit state.

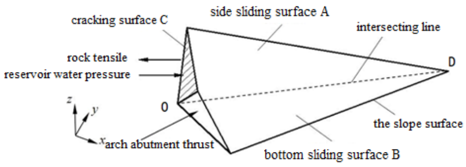


Fig.1. The geometry and force diagram of wedge

The forces acting on the wedges are projected onto the normal directions of the A and B planes and the direction of the intersecting line. The equilibrium equation is as follows:

$$(N_a + U_A) + m_{nb,na}(N_b + U_B) + m_{w,na}W + m_{v,na}V + m_{t,na}T = 0 \quad (1)$$

$$(N_b + U_B) + m_{na,nb}(N_a + U_A) + m_{w,nb}W + m_{v,nb}V + m_{t,nb}T = 0 \quad (2)$$

$N_a$ , $N_b$ mean effective normal reaction on surface A and surface B, and unit vector are $\boldsymbol{n_a}, \boldsymbol{n_b}$ ; $U_a$ , $U_b$ mean uplift pressure on surface A and surface B; $W$ means the weight of wedge body, and unit vector is $\boldsymbol{w}$ ; $V$ means the sum of tensile strength and water pressure on crack surface; $T$ means arch abutment thrust of wedge body, and unit vector is $\boldsymbol{t}$ ; $S$ means slip force of wedge body in intersection direction, and unit vector is $\boldsymbol{j}$ .

Combine equation (1) and (2), $N_a$ and $N_b$ can be got:

$$N_a = qW + rV + sT - U_A \quad (3)$$

$$N_b = xW + yV + zT - U_B \quad (4)$$

In these equations，

$$q = (m_{na,nb}m_{w,nb} - m_{w,na})/(1 - m^2{}_{na,nb})$$

$$r = (m_{na,nb}m_{v,nb} - m_{v,na})/(1 - m^2{}_{na,nb})$$

$$s = (m_{na,nb}m_{t,nb} - m_{t,na})/(1 - m^2{}_{na,nb})$$

$$x = (m_{na,nb}m_{w,na} - m_{w,nb})/(1 - m^2{}_{na,nb})$$

$$y = (m_{na,nb}m_{v,na} - m_{v,nb})/(1 - m^2{}_{na,nb})$$

$$z = (m_{na,nb}m_{t,na} - m_{t,nb})/(1 - m^2{}_{na,nb})$$

So we can get the slip force,

$$S = m_{w,j}W + m_{v,j}V + m_{t,j}T$$

The stability safety factor of wedge is,

$$K = \frac{c_A \cdot A_A + c_B \cdot A_B + N_a \cdot \tan\phi_a + N_b \cdot \tan\phi_b}{S} \quad (5)$$

$c$ , $\phi$ mean cohesion and friction angle on the sliding surface of wedge. $A_A, A_B$ mean the area of surface A, surface B. If $K < 0$ , The wedge is in a superstable state.

## 3. Engineering example

In combination with an arch dam engineering example[5], the improved dynamic stability analysis method is applied to the safety assessment of dam abutment. The rationality of the calculation method is proven through a comparison of safety factors.

### *3.1. Project Overview*

In a triple-core, roller compacted concrete (RCC) gravity arch dam, the maximum dam height is 130.0

m. The rocks are generally weakly weathered and unloaded due to the strong weathering and unloading at certain high elevations. The integrity of granite schists and hornfels is good, and their strength is high. The rest of the rocks are relatively fragile and weak.

On May 12, 2008, an 8.0 magnitude earthquake occurred near the town of Ying Xiu town in Wen Chuan County, Sichuan Province. The dam site was 36 km away from the epicenter. The dam showed no major visible damage after the high-intensity long-lasting earthquake.

The comprehensive strength indexes of the slip boundary condition in each resisting rock mass are shown in Table 1.

Table 1. Comprehensive strength indexes of potential slip surfaces in each group

| Boundary structure plane | | Shear strength prior to cracking | | Shear strength | |
|---|---|---|---|---|---|
| | | *f'* | *C'* (MPa) | *f* | *C* (MPa) |
| Left bank | Lateral cutting surface | 0.89–0.99 | 0.54–0.86 | 0.66–0.74 | 0 |
| | Bottom slip surface | 0.99–1.11 | 0.68–1.10 | 0.70–0.80 | 0 |
| Right bank | Lateral cutting surface | 0.89–1.00 | 0.55–0.88 | 0.67–0.75 | 0 |
| | Bottom slip surface | 0.99–1.12 | 0.70–1.13 | 0.71–0.82 | 0 |

### *3.2. Parameters and conditions of the calculation*

1, Material parameters

The foundation material parameters used in the calculation are shown in Table 2. The bulk density, deformation modulus, and Poisson's ratio of concrete are 2,400 kg/m$^3$, 18 GPa, and 0.167, respectively. The Poisson's ratio of bedrock is 0.25. The initial gap of transverse joints is set to 0, and the friction coefficient is 0.7. The cohesion and tensile strength of the seam are not considered. In the dynamic analysis, the dynamic elastic modulus increases in static modulus on the basis of 30%.

Table 2. Basic overall deformation modulus and dam body temperature

| Elevation (m) | Left bank | Right bank | *Tm* (°C) | *Td* (°C) |
|---|---|---|---|---|
| 1867.5 | 13.5 | 6 | –6.56 | 0 |
| 1850 | 13.5 | 6 | –2.97 | 2.27 |
| 1830 | 13.5 | 6 | –1.91 | 2.66 |
| 1810 | 13.5 | 8.5 | –1.44 | 3.65 |
| 1790 | 13.5 | 13.5 | –1.20 | 4.33 |
| 1770 | 13.5 | 13.5 | –1.11 | 4.5 |
| 1750 | 13.5 | 13.5 | –0.99 | 4.3 |

Note: *Tm* and *Td* are the average temperature and equivalent temperature of the dam body, respectively. Downstream face temperature minus upstream face temperature equals *Td*.

2. Conditions and loads

Under a normal water level, the elevation of the upstream water level is 1,866.0 m, and the corresponding downstream water level elevation is 1,750.0 m. The silt elevation in the upstream is 1,796.0 m, the submerged unit weight of silt is 5.0 kN/m$^3$, and the internal friction angle is 0°. The temperatures of different elevations are also shown in Table 2.

The accelerations of seismic waves in three directions vary with time and are illustrated in Figure 2. In summary, the calculation conditions are a combination of normal water level, corresponding

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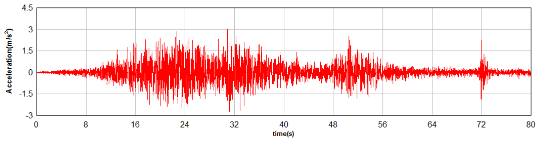
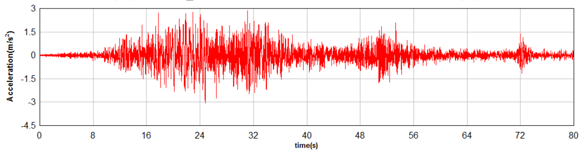
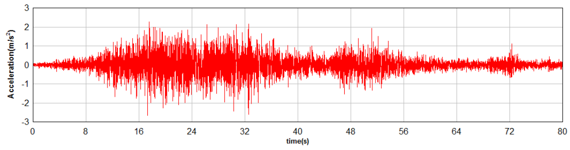
upstream water level, gravity, silt pressure, seepage pressure, changes in temperatures, and design earthquake.



(a) Perpendicular to the river (*x*)



(b) Along the river (y)



(c) Vertical upward (z)

Fig.2. Acceleration of seismic waves in three directions.

*3.3. Finite element model*

The model uses a Cartesian coordinate system, and the positive axis is defined as follows. The x axis is the direction of the dam axis and points to the left bank as positive. The y axis is along the river and points upward as positive. The z axis is vertical and points upward as positive. The dam body is divided into four layers of grids along the thickness direction, 13 layers of grids along the height direction, and four transverse joints in the dam body. The transverse joints are numbered from the left bank to the right bank sequentially. The total calculation model consists of 43,186 nodes and 39,343 hexahedron units.

Generally, seismic acceleration is collected from the surface. In this method, the seismic waves are imported through the basement. Consequently, a suitable foundation area should be selected to eliminate the amplification effect of seismic waves on the foundation. According to a similar engineering experience, the area selected in the study is 1.5 times the height of the dam along the left and right banks, 2 times the height of the dam upstream and downstream, and 1.5 times the depth of the dam below the foundation. The overall model is presented in Figure 3.

In the static calculation, the foundation boundary is fixed, and the lateral boundary is normally constrained. Correspondingly, in the dynamic calculation, considering the influence of foundation radiation damping, the viscoelastic artificial boundary is set on the foundation.

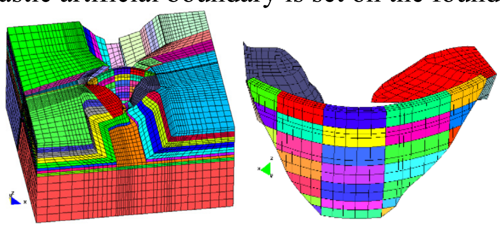


Fig.3. Dam body and overall finite element model diagram.

## 4. Result analysis of dynamic calculation

This method is a combination of finite element and rigid body limit equilibrium methods[6]. The calculation steps are as follows:

1, The abutment thrust over time is calculated. The calculation of thrust in static and dynamic conditions is carried out, and the most unfavorable results are overlaid.

2, The seismic inertial force is calculated. The seismic inertial force is generally equal to the horizontal designed seismic peak acceleration multiplied by the mass of abutment rock and the vertical designed seismic peak acceleration multiplied by the mass of abutment rock. Considering that the force cannot reach the maximum at the same time, the method introduces the binding coefficient to combine the force. The combinations are shown in Table 3.

3, The change in safety factor over time is calculated. The safety factors of each moment are calculated by the combinations of the arch thrust at different times and different inertial forces. The curve of the safety factor is obtained. Similarly, the factor is obtained using the formula of the rock wedge safety factor.

For example, in combination 1, the safety factor over time on the right bank is shown in Figure 4. And the left in Figure 5. Table 3 indicates that the safety factor of the right bank is higher than that of the left bank, that is, the seismic stability on the left bank is poor.

Table 3. Minimum safety factor obtained by the finite element rigid limit equilibrium method

| Rock number | | | | L | R |
|---|---|---|---|---|---|
| Combination 1 | x = 0.5 | y = 1.0 | z = 1.0 | 2.965 | 3.511 |
| Combination 2 | x = 1.0 | y = 0.5 | z = 1.0 | 2.429 | 3.496 |
| Combination 3 | x = 1.0 | y = 1.0 | z = 0.5 | 2.559 | 3.182 |

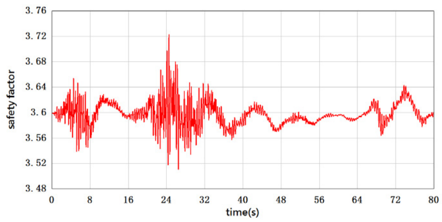



Fig.4. Safety factor over time on the right bank.
(Combination 1)

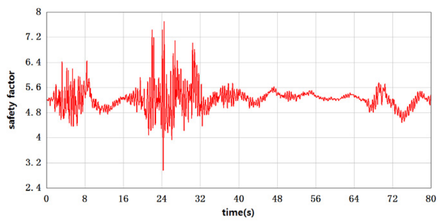



Fig.5. Safety factor over time on the left bank.
(Combination 1)

## 5. Conclusions

The finite element dynamic time history method is used to calculate the arch abutment thrust, so the method can initially reflect the changes in magnitude and direction. The method also considers the binding coefficient and partly reflects the random effects of the earthquake. The result of dynamic stability analysis of shapai arch dam effected by wenchuan earthquake is that the safety factor of the right bank abutment rock mass is higher, and the left seismic stability is poorer. The method used in this paper can reflects the actual working state of the dam abutment and in the safety stability evaluation of arch dam abutment is highly reasonable.

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