Study on numerical simulation method of overtopping dam break of concrete faced sand-gravel dam

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Abstract. Based on the field investigation of dam break cases, a numerical simulation method of concrete faced sand-gravel dam overtopping break is proposed. The method is mainly composed of three parts: (1) Aiming at the erosion and scour of vortex flow on dam body, appropriate model is used to simulate the flow movement; (2) The interaction between water flow and sand particles in dam break process is accurately simulated; (3) Based on moment balance method, the failure process of concrete face slab under dead weight and water load is determined. The results show that the proposed mathematical simulation method can accurately simulate the reverse erosion of the dam and the detailed evolution of the face slab break during the dam break process. The relative error between the measured data and the calculated peak breach flow, the development of the breach of the rockfill body, the duration of the dam break and the length of the face slabs are all less than 15%, which verifies the rationality of the numerical model.

1. Introduction

Because of its short construction period, local materials and strong adaptability to terrain and geological conditions, concrete faced sand-gravel dam (CFSGD) has gradually become a competitive dam type[1-2]. However, the anti-erosion performance of sandy gravels is poor[3]. Once the reservoir water overflows due to excessive flood or landslide in the reservoir area, the CFSGD is likely to break. In order to reduce the serious consequences caused by the crash, it is of great significance to carry out numerical simulation research on the overtopping dam break of the CFSGD.

The investigation results after the dam break of Gouhou reservoir and Taum Sauk Upper reservoir show that the vortex erosion of the dam body, the reciprocating fracture of the face slab and the instability of the breach slope are the three main characteristics of the dam break of the CFSGD. Liu[4] found out the cause of the failure of Gouhou dam through flume model test, but did not reveal the failure mechanism of the dam after reservoir water overtopping. Li[5] established a simplified mathematical model of dam break by using the erosion formula proposed by Singh, but the failure of the breach slope was not considered. Wang et al.[6] considered the influence of sediment content change in the discharge flow on the dam break process, and established a moving bed coupling analysis model, but the analysis of face slab fracture was simplified. Based on the investigation of actual dam break cases and centrifugal model tests, Chen et al.[7] and Zhong et al.[8-9] studied the transport of sandy gravel materials and the damage of concrete face slab in detail, and proposed the mathematical model of overtopping dam break of CFSGD, but ignored the erosion and scouring effect of vortex flow on the dam body.
Based on the field investigation of dam break cases and analysis of previous research results, this paper focuses on the erosion characteristics between vortex water flow and sandy gravel materials, and simulates the erosion evolution process of the dam under the action of vortex water flow through the sediment transport formula and turbulence model, and bending moment balance method is used to determine the breach evolution of concrete face slab, a mathematical model that can reflect the interaction among water flow characteristics, sandy gravel materials and concrete face slab is established. The detailed results of the mathematical model of dam break are very important for the development of appropriate early warning system and emergency response plan.

2. Mathematical model of dam break

2.1. RNG k-ε turbulence model
In the process of the dam break of CFSGD, the flow of dam break violently scours in the lower area of the face slab, and the sand-laden flow is turbulent, so the turbulence model should be used to simulate the dam break flow. The RNG k-ε turbulence model considers the rotation of water in the flow, and can better improve the degree of streamline curvature in the flow field. The basic control equation[10] is:

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \mu + \frac{\mu_t}{\sigma_k} \frac{\partial k}{\partial x_j} \right] + G_k - \rho \varepsilon
\]

(1)

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \mu + \frac{\mu_t}{

2}\varepsilon \right] + C_1 \frac{G_k}{k} - C_2 \frac{\rho \varepsilon^2}{k}
\]

(2)

Where \( t \) is the time, \( \mu \) is the turbulent viscosity coefficient, \( C_\mu = 0.085 \), \( G_k \) is the production term of turbulent kinetic energy \( k \).

2.2. Sediment transport and erosion
During the whole process of dam break, the movement state of sand particles is transformed between suspension and deposition. Because it is impossible to calculate the movement of a single particle in the fluid, the empirical formula should be used to calculate the sand transport. In this paper, the suspended load motion and bed load motion of sand particles are calculated based on the lifting velocity equation[11] and Meyer Peter & Muller equation[12]. The equations are as follows:

\[
u_{i\theta,j} = \alpha n_s d_*^{0.5} \left( \theta_i - \theta_{cr,i} \right)^{1/2} \left[ g \left( \frac{\rho_s - \rho}{\rho} \right) d \right]^{1/2}
\]

(3)

\[
q_b = \beta \left( \theta_i - \theta_{cr,j} \right)^{1/2} \left[ g \left( \frac{\rho_s - \rho}{\rho} \right) d_j \right]^{1/2}
\]

(4)

Where \( n_s \) is the vertical direction of the slope, \( d_* \) is the dimensionless particle size parameter, \( \theta_i \) is the bed surface shields number, \( \theta_{cr,i} \) is the critical shields number, \( d \) is the average particle size, \( \alpha_s = 0.0018 \), \( \beta = 8 \).

2.3. Face slab fracture analysis
In the process of concrete faced sand-gravel dam break, when the concrete face cannot bear the action of dead weight and water load, the face slab will fracture. In this paper, the face slab is assumed to be a cantilever slab, and the bending moment balance method is used to determine the fracture of concrete face slab. The bending moment \( M_1 \) caused by the dead weight of the face slab can be expressed as:

\[
M_1 = \frac{\rho_{mg} m_l \delta W T_{w,d}^2}{2 \sqrt{1 + m_l^2}}
\]
Where $\rho_m$ is the density of concrete face slab, $m_1$ is the upstream slope ratio, $\delta$ is the equivalent thickness of face slab, $L_d$ is the limit length of face slab breaking.

The bending moment $M_2$ of water load acting on the face slab can be expressed as[9]:

$$
M_2 = \frac{\rho_m g w(z_s - z_f) L_d^2}{2} + \frac{\rho_m g w L_d}{6\sqrt{1 + m_1^2}} z_s > z_f
$$

$$
M_2 = \frac{\rho_m g w [L_d - (z_f - z_s)]^3}{6\sqrt{1 + m_1^2}} z_s < z_f
$$

(6)

The ultimate bending moment $M_f$ of the concrete face slab can be calculated according to the design code, then the determination condition of the slab fracture is:

$$
M_i + M_2 > M_f
$$

(7)

3. Case study

3.1. Establishment of numerical model

In order to verify the rationality of the mathematical model established in this paper, according to the topographic map of Gouhou dam, the numerical calculation model is established according to the scale of 1:1. The maximum dam height of Gouhou dam is 71m, the total length of dam crest is 265m, the width of dam crest is 7m, the upstream side of dam crest is provided with 5m high "L" shaped concrete wave wall, the upstream slope ratio is 1:1.6, and the downstream slope ratio is 1:1.5. The basic section of the dam is shown in Figure 1. In order to ensure the calculation accuracy and improve the calculation efficiency, structured grid is used to divide the calculation area of the model into three grid blocks, as shown in Figure 2. Grid block 1 is the reservoir area, the grid size is 4m×4m×4m, grid block 2 is the concrete faced sand-gravel dam, the 2m×2m×2m grid is used for local encryption, and grid block 3 is the downstream terrain. Because the downstream computing domain is not the key area, the 6m×6m×6m grid is used for division, and the total number of grid cells is about 4.94 million.

3.2. Calculation parameters of sandy gravels and face slab

The average maximum particle size of Gouhou dam material is 400mm, the minimum particle size is 0.1mm, the median particle size is 12.0mm, the density is 2.08g/cm$^3$, the internal friction angle is 40°, and the angle of repose is 60°. The basic parameters of the face slab are obtained by consulting literature[8-9], which are shown in Table 1.

| $\rho_m$ (kg/m$^3$) | $w$ (m) | $\delta$ (m) | $f_y$ (N/m$^2$) | $h_0$ (m) | $f_c$ (N/m$^2$) | $A_c$ (m$^2$) |
|---------------------|---------|--------------|-----------------|------------|----------------|--------------|
| 2600.0              | 14.0    | 0.35         | $3.0 \times 10^4$ | 0.175      | $9.6 \times 10^6$ | 0.018        |
4. Calculated results analysis

4.1. Evolution process of dam break
The whole dam break process of Gouhou dam is shown in Figure 3. It can be seen from the figure that the numerical simulation results are basically consistent with the dam break characteristics of physical model test. With the collapse of the 5m high wave wall, the initial breach at the top of the dam was gradually cut down, and a gully was gradually formed on the downstream dam slope. Due to the existence of reinforced concrete face slabs, when \( t = 4700 \)s, waterfall-like water flow was formed at the dam crest, and the rockfill body appeared obvious scouring pits. When the suspended length of the face slab reaches the limit breaking length, the face slab breaks, and the breaking of the face slab makes the cross-section and vertical section of the breach expand rapidly. When \( t = 5240 \)s, the reservoir water level is not yet stable, but the erosion has reached the riverbed, and then the rockfill will mainly expand laterally. When \( t = 7200 \)s, the reservoir water level tends to be stable, and the dam break process basically over.

![Figure 3. Failure process of Gouhou concrete faced sand-gravel dam](image)

4.2. Comparison of measured and predicted results
It is obvious from Figure 4 that the discharge hydrograph of the breach calculated in this paper is not a smooth curve, but a curve with multiple peaks. The reason is that in the process of dam break, the face slab has a certain water retaining capacity, which makes the reservoir water level change less in a period of time. When the face slab breaks, the upstream reservoir water level drops sharply in a short time, and the breach flow increases suddenly. Then the face slab plays a role of water retaining again, and the breach flow will decrease to a certain extent. Because the failure of the concrete face slab is a process of multiple fracture, there will be multiple peaks in the discharge hydrograph of the dam breach.

![Figure 4. Breach discharge process line](image)
The actual field investigation results show that the peak discharge time of Gouhou dam at 22:40 on August 27 (1.46h from the initial overtopping dam break), the peak discharge of dam break was 3267m³/s, the dam break duration was 1.83h–2.25h, the final dam crest width of rockfill dam breach is 137.5m, the dam bottom width is 61.0m, and the breach depth is 60.0m. The mathematical model established in this paper is used to calculate the breach discharge process of Gouhou dam, the breach discharge process line is shown in Figure 1. The predicted peak discharge is 3492.3m³/s, and the relative error is 6.9% compared with the measured value of 3267m³/s. The expansion process of dam crest breach is shown in Figure 5, it can be seen that the calculated width and depth of rockfill breach are 132.5m and 69m respectively. Compared with the measured value, the relative errors are 3.6% and 15% respectively, which are close to the measured value.

The model established in this paper can well describe the coupling effect between water and soil, so that the calculation results can effectively reflect the dam break process and predict more accurately, which is also the obvious difference between the model in this paper and the simplified mathematical model. It can be seen from the discharge hydrograph of the breach that there were about 7 large-scale fracture of the face slab after the dam break, and the whole dam break lasted about 2 hours.

![Figure 5](image.jpg)

Figure 5. The process of width and depth of breach: (a) Breach width, and (b) Breach depth.

5. Conclusions
In this paper, a numerical method is proposed to simulate the overtopping failure of concrete faced sand-gravel dam based on the case study of concrete faced sand-gravel dam and the analysis of previous research results. This method is used to simulate the overtopping failure of Gouhou dam, and the calculation results are compared with the detailed measured data to verify the rationality of the numerical method. The characteristics of this method are as follows:

(1) This method emphatically considers the erosion characteristics between the vortex flow and the sandy gravel materials. The reverse erosion of the face slab support by the vortex flow is simulated in detail through RNG $k$-$\varepsilon$ turbulence model and sediment transport formula. The interaction among the flow characteristics, sandy gravel materials and concrete face slab during the dam break process is also reflected, and the failure mechanism of the concrete faced sand-gravel dam is further revealed.

(2) The relative error between the measured data and the calculated peak breach flow, the development of the breach of the rockfill body, the duration of the break and the length of the face slabs are all less than 15%, while the transverse expansion of rockfill breach is slightly different, but on the whole, the numerical results are basically consistent with the actual results, which verifies the rationality of the numerical model.

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