Back Analysis of Banqiao Clay Core Dam Breaching

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Abstract

In this study, a numerical model is put forward to simulate the Banqiao reservoir dam breaching. Based on the breaching process records, a numerical model is put forward. In this model, two different erosion formulas are utilized to simulate the erosion process of dam shell and core materials, respectively; a mechanical equilibrium equation is adopted to simulate the shear failure of clay core; meanwhile, broad-crested weir formula is adopted to calculate breach flow discharge, the limit equilibrium method is utilized to analyze the stability of breach slope as well. In addition, according to the real situation, the model considers dam base erosion. Based on the surveyed records, the calculated results of the proposed model are in accordance with the measured data.
Keywords: Banqiao reservoir, overtopping, clay core dam, numerical model.

1. INTRODUCTION

Based on the Bulletin of First National Census for Water [1], by the end of 2011, there is 98002 reservoir dams in China; on the contrast, according to the statistical data of Dam Safety Management Center of the Ministry of Water Resources, P. R. China [2], from 1954 to 2014, there have been 3530 dam breach accidents happened in China. According to the statistics, the dam breach accidents of overtopping failure occupy over 50% of the total number. In August 1975, the clay core dam with a height of 24.5 m of Banqiao reservoir was failed due to overtopping flow, the dam breached resulting in catastrophic downstream flooding and over 26000 fatalities [3]. In order to evaluate the consequence of the core dam breaching, the mechanism of clay core dam breach due to overtopping failure requires in-depth research, as well as the mathematical model which can reasonably simulate the breach process.

As we know, for the homogeneous dam overtopping failure, numerous tests of different scales are carried out, an array of numerical models are put forward [4]. When it comes to core dam overtopping failure, owing to the complexity of the model test, only the IMPACT Project [5] and NHRI [6] held a large scale model test of moraine core rockfill dam with a height of 6.0 m and centrifugal model tests of clay core rockfill dam with a height of 16.0 m, respectively (see Figures 1 and 2).

Figure 1. Large scale model test of moraine core rockfill dam due to overtopping failure

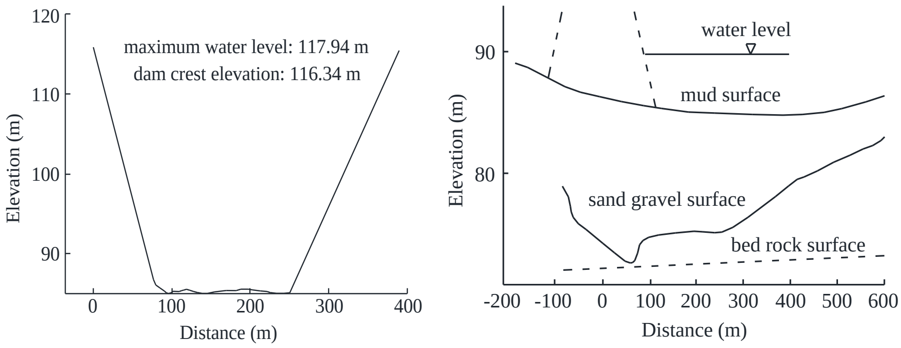
Figure 2. Centrifugal model test of clay core rockfill dam due to overtopping failure

The model tests show that the overtopping flow first erodes the downstream dam shell. With the increasing erosion of the downstream dam shell, the downstream side of the core is gradually exposed and hollow. Under the co-action of the upstream water and soil pressures, shear failure occurs in the core. With the decrease of water head, the discharge through the breach gradually fall to zero.

Since 1980s, according to the soil erosion tests, some mathematical model for core dam breaching are put forward. Among these models, NWS BREACH model [7], HR BREACH model [8, 9], DLBreach model [10], and NHRI-CCOB model [6] are the representatives.

It is worth mentioning that the subbase erosion of the dam is not considered in the core dam breaching model tests at home and abroad. Figure 3 shows the final breach of the Banqiao reservoir dam, owing to the erodible base and large reservoir storage and relative small dam height, the base erosion depth is 5.04 m (see Figure 4(a)). Meanwhile, a scour hole which has a depth of 11.0 m is formed downstream, then the hole is filled with reservoir deposit (see Figure 4(b)). In order to simulate the clay core dam breaching process of Banqiao reservoir, a mathematical model is put forward, the technical details are described in the following sections.

Figure 3. Final breach of Banqiao reservoir dam



(a) vertical section (b) cross section

Figure 4. Breach sections of Banqiao reservoir

2. BREACHING PROCESS OF BANQIAO CLAY CORE DAM

Banqiao reservoir has a maximum storage of 4.92×10^8 m^3, and a maximum dam height of 24.5 m as well. The length of the dam is 2020 m, and the crest width is 6 m. The dam crest and the wave wall elevations are 116.34 m and 117.64 m, respectively.

In August 1975, a heavy storm occurs in Henan. When it comes to Banqiao reservoir, there are two inflow process, the first inflow occurs during 14:00 August 5th to 2:00 August 6th, and the peak inflow is 7500 m^3/s; the second inflow occurs during 12:00 August 7th to 8:00 August 8th, and the peak inflow is 13000 m^3/s (see Figure 5).

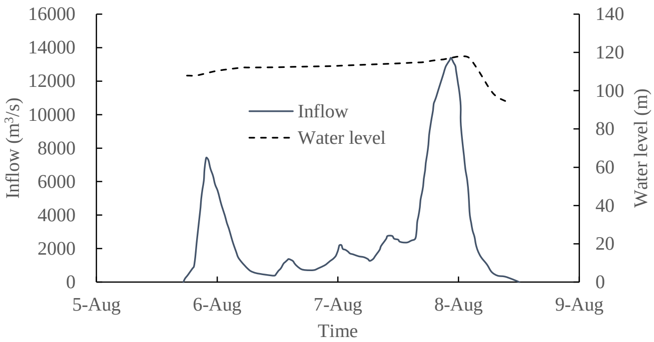


Figure 5. Inflow and water level variation of Banqiao reservoir during "75.8" flood

3. NUMERICAL MODEL FOR BANQIAO CLAY CORE DAM BREACHING PROCESS

In this section, a numerical model is proposed to simulate the breaching process of Banqiao clay core dam. Based on the model tests, the breach mechanism of clay core dam due to overtopping failure is revealed. The breach is divided into two reaches at the early stage before the clay core is exposed (see Figure 6, ①-②). Once the core is exposed, the breach is divided into three reaches (see Figure 6, ③-⑥); then, the clay core may fail due to significant erosion in the lower shoulder reach. After the core failure, the breach is divided into two reaches again (see Figure 6, ⑦-⑨). After the remaining material in the breach is washed out and the non-erodible foundation is exposed, the breach can still widen until the headwater is depleted or the tailwater is raised.

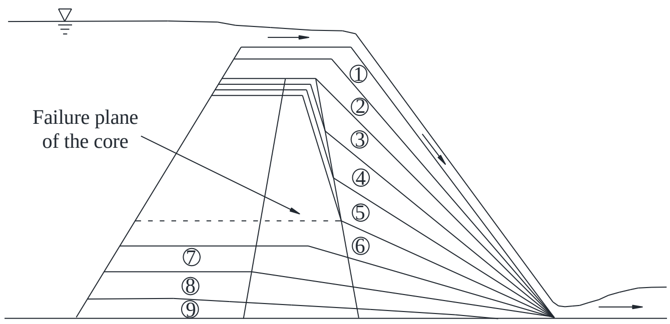


Figure 6. The breaching process of clay core dam due to overtopping failure

Based on the mechanism of dam breach process described above, a numerical model is put forward for clay core dam breach due to overtopping failure. The technical details are described as follows.
The water balance in the reservoir can be described by:

$$\frac{dV}{dt} = A_s \frac{dz_s}{dt} = Q_{in} - Q_b - Q_{spill} - Q_{sluice} \tag{1}$$

Where V=volume of water in the reservoir; t=time; A_s=surface area of reservoir; z_s=water surface elevation; Q_{in}=inflow discharge; Q_b=breach flow; Q_{spill}=flow through spillways; and Q_{sluice}=flow through sluice gates.

The reservoir geometric characteristics are represented by the surface area and water depth curve, $z_s(h)$. The curve is usually given as pair values of surface area and water depth in the reservoir.

The overtopping flow at the breach is estimated using the broad-crested weir equation:

$$Q_b = k_{sm}\left(c_1 b h^{1.5} + c_2 m h^{2.5}\right) \tag{2}$$

Where b=bottom width of the breach; h=z_s-z_b, z_b=elevation of breach bottom; m=side slope (horizontal/vertical) of the breach; c_1=1.7, c_2=1.3 [11]; and k_{sm}=submergence correction for tailwater effects on weir outflow. k_{sm} is determined with the empirical relationship [11, 12].

Two erosion formula are utilized to deal with the erosion of dam shell material and clay core material, respectively.

For the dam shell material, it is assumed to be a noncohesive material and the erosion is calculated using the following formula which is put forward based on the steep channel model tests [6]:

$$Q_s = 0.25\left(\frac{d_{90}}{d_{30}}\right)^{0.2} B_b \sec\theta \frac{v_*\left(v_b^2 - v_c^2\right)}{g\left(\frac{\gamma_d}{\gamma_w} - 1\right)} \quad (3)$$

Where Q_s=erosion volume; d_{90}=particle size for which 90 percent is finer by weight; d_{30}=particle size for which 30 percent is finer by weight; B_b=width of breach bottom; θ=downstream slope angle; v_*=friction velocity; v_b=flow velocity at breach bottom; v_c=incipient velocity of dam material; γ_d= specific gravity of soil, in this paper, it is assumed to be 2.65×9.8kN/m^3; and γ_w=specific gravity of water, in this paper, it is assumed to be 9.8kN/m^3.

The erosion rate of dam shell material can be calculated as follows:

$$\left(1 - p'\right)\frac{dV_b}{dt} = \frac{dQ_s}{dt} \quad (4)$$

Where p'=porosity of dam shell material; and dV_b/dt=erosion rate of dam shell material.

It is assumed that the breach slope angle is equal to the internal friction angle, the relationship between horizontal expansion and vertical undercutting is determined by (see Figure 7):

$$\Delta b = \frac{n_{1oc}\Delta z_b}{\sin\varphi_1} \quad (5)$$

Where Δb=horizontal expansion value at each time step; Δz_b=vertical undercutting value at each time step; n_{loc}=indicator of breach location (n_{loc}=1 for one-sided breach and 2 for breach located at the middle of dam length); and φ_1=internal friction of dam shell material.

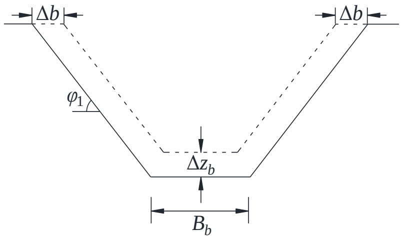


Figure 7. Breach development of dam shell

When it comes to the clay core, the erosion at the breach top flat section is computed using the following excess shear detachment rate relation [13]:

$$\frac{dz}{dt} = k_d\left(\tau_e - \tau_c\right) \quad (6)$$

Where dz/dt=erosion rate; k_d=erosion coefficient; τ_e=bed shear stress; and τ_c=critical stress required to initiate detachment for the material determined using Shields diagram.

The coefficient k_d usually needs to be measured [14-16] or utilizes the empirical formula [17]:

$$k_d = \frac{5.66\gamma_w}{\gamma_d}\exp\left[-0.121c\%^{0.406}\left(\frac{\gamma_d}{\gamma_w}\right)^{3.1}\right] \quad (7)$$

Where $c\%$=clay ratio.

The bed shear stress is determined by using the Manning equation:

$$\tau_e = \frac{\rho_w g n^2 Q_b^2}{A^2 R^{\frac{1}{3}}} \quad (8)$$

Where ρ_w=water density; A=flow area; R=hydraulic radius. The Manning's n is relate to sediment median size d_{50} (m) by:

$$n = \frac{d_{50}^{\frac{1}{6}}}{A_n} \quad (9)$$

Where A_n is an empirical coefficient. In this model, A_n=12 for the field cases [10].

The width change of the breach can be assumed as follows:

$$\Delta b = n_{1oc} \Delta z_b \tag{10}$$

With the erosion of dam shell and clay core, the downstream side of the core is gradually exposed and hollow. Under the co-action of the upstream water and soil pressures, shear failure occurs in the core (see Figure 8(a)). The stress state of the failure clay core is shown in Figure 8(b).

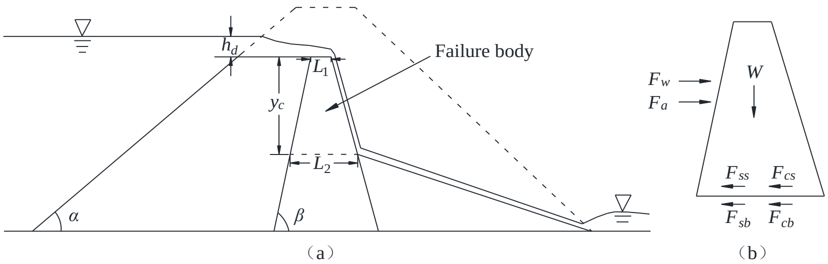


Figure 8. Shear failure of clay core

As shown in Fig. 9, the critical condition of clay core failure can be expressed as:

$$F_a + F_w = F_{sb} + F_{ss} + F_{cb} + F_{cs} \tag{11}$$

In which,

$$F_a = 0.5 B_b y_c \left[\gamma_1 y_c \tan^2\left(45^\circ - \frac{\varphi_1}{2}\right) - 2c_1 \tan\left(45^\circ - \frac{\varphi_1}{2}\right) \right] \tag{12}$$

$$F_w = 0.5 \gamma_w B_b \left(y_c + h_d \right)^2 \tag{13}$$

$$F_{sb} = W \tan \varphi_2 \tag{14}$$

$$F_{ss} = \gamma_2 y_c^2 K L_2 \tan \varphi_2 \tag{15}$$

$$F_{cb} = C_2 B_b L_2 \tag{16}$$

$$F_{cs} = C_2 y_c \left(L_1 + L_2 \right) \tag{17}$$

$$B_b = B_t - 2 y_c \cot \varphi_1 \tag{18}$$

$$K = \frac{1 - \sin \varphi_2}{1 + \sin \varphi_2} \tag{19}$$

$$L_2 = L_1 + 2 y_c \cot \beta \tag{20}$$

$$W = 0.5 \gamma_2 \left(L_1 + L_2 \right) B_b y_c \tag{21}$$

Where F_a=active earth pressure of the dam materials upstream the clay core; F_w=water pressure; F_{sb}=friction along the bottom of failure plane; F_{ss}=friction along the two sides of failure plane; F_{cb}=cohesion along the bottom of failure plane; F_{cs}=cohesion along the two sides of failure plane; h_d=the water head above the dam crest; y_c=the height between dam crest to failure plane of clay core; K=coefficient of static earth pressure; B_t= breach top width; B_b=breach width at the failure plane; L_1=top width of clay core; L_2=width of failure palne; W=clay core weight above failure plane; γ_1=dry specific gravity of dam shell material; γ_2=dry specific gravity of clay core material; C_1=cohesion of dam shell material; C_2=cohesion of clay core material; α=slope angle of dam upstream; β=slope angle of clay core upstream; φ_1=internal friction angle of dam shell material; φ_2=internal friction angle of clay core material.

In the case of erodible foundation, the model allows erosion into the foundation. The breach is assumed to have a flat horizontal bottom surface and can lower to a value predefined according to the foundation material properties, but the base erosion does not affect the upstream water volume and downstream channel flow. The breach flow discharge is determined using Eq. (2) with submergence coefficient considered. As erosion continues into the foundation, breach widens laterally until the breaching is finished.

4. CALCULATE RESULTS ANALYSIS

The following section analyzes the results of the breaching process of Banqiao reservoir dam failure using the model above-mentioned. The dam configurations, reservoir characteristics, and soil properties are shown in Table 2. The calculated results of peak breach flow (Q_p), breach top width (B_t), breach bottom width (B_b), time to peak discharge (T_p), failure time (T_f), and measured data (Xu and Zhang 2009; Ru and Niu 2001) are shown respectively in Table 3, Figures 9 and 10 also show the calculated breach flow hydrograph and the breach development of Banqiao reservoir dam.

Table 2- Conditions of Banqiao reservoir dam failure case

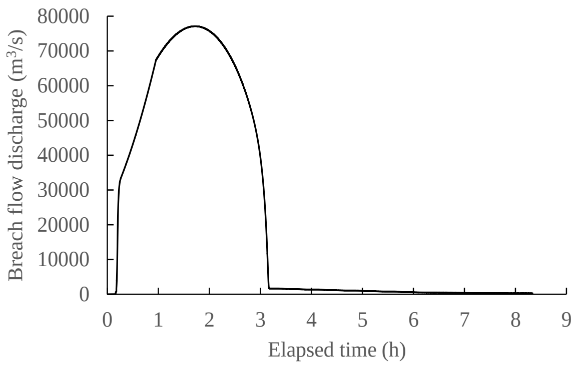
Parameter	Value
Dam height (m)	24.5
Dam length (m)	500
Crest width (m)	8
U/S slope (V/H)	0.384
D/S slope (V/H)	0.5
Reservoir storage (m^3)	6.08×10^8
Reservoir surface area (m^2)	A_s-h
Initial reservoir level (m)	26
Inflow (m^3/s)	Q_{in}-t
Base erosion (m)	-5.04
k_d (cm^3/N-s)	18
τ_c (Pa)	0.5
Clay core	
Height (m)	23[a]
Crest width (m)	3[a]
U/S slope (V/H)	4[a]
D/S slope (V/H)	4[a]
d_{50} (mm)	0.03[a]
p'	0.3
C (kPa)	30[a]
φ (°)	26.6[a]
Clay ratio	0.4[a]
d_{90}/d_{30}	10[a]
Dam shell	
d_{50} (mm)	0.2
p'	0.35
C (kPa)	0
φ (°)	20[a]
d_{90}/d_{30}	20[a]

Note: U/S=upstream slope=vertical/horizontal, D/S=downstream slope=vertical/horizontal.
[a]Assumed value.

Table 3- Results of Banqiao reservoir dam failure case

Calculated results					Measured data				
Q_p (m^3/s)	B_t (m)	B_b (m)	T_p (h)	T_f (h)	Q_p (m^3/s)	B_t (m)	B_b (m)	T_p (h)	T_f (h)
77085.1	432.4	286.4	1.72	3.03	78100	372	210	-	5.5

Note: The calculated failure time is defined as the time period from the beginning of dam breaching to the moment when 99% of the final breach width is reached.



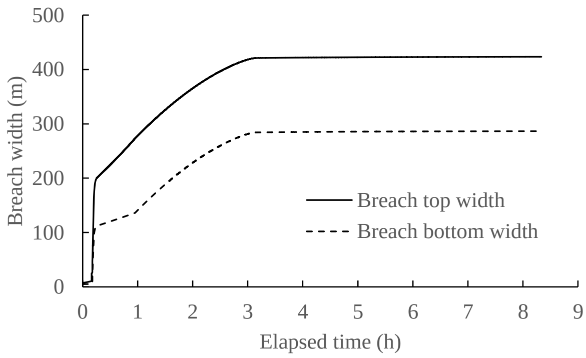


Figure 9. Calculated breach flow discharge **Figure 10. Breach width development**

Based on the contrast table and the figures, some conclusions can be drawn. According to Figures 9 and 10, owing to the collapse of wave wall, the overflow water head is about 1.5 m above the dam crest, the breach flow discharge increases immediately at the initial breaching period, as well as the top and bottom breach widths; after 1.72 h, the peak discharge occurs, then the breach flow decreases, and the breach width increases relatively small until the end of breaching. According to Table 3, the calculated peak breach flow is 77085.1 m^3/s, which is 1.3% smaller than the measured data. To the breach widths, we can see that the breach top width and breach bottom width is 16.2% and 36.4% larger than the measured data, respectively. When it comes to the failure time, the calculated data is 44.9% smaller than the measured one. Overall, the calculated peak discharge is in accordance with the measured data; in contrast, the calculated breach widths are larger than measured data especially the bottom breach width, the possible reason is the drainage of reservoir sediment affects the development of breach; owing to the lacking of measured time to peak, the contrast of this parameter is ignored; with regard to failure time, the definitions of calculated and measured data are different, the documentary record is the duration of whole breaching process, which differs to the calculated failure time. From the above, the numerical model can meet the demands in calculating of Banqiao reservoir dam breaching process.

5. CONCLUSION

A numerical model is proposed to calculate the Banqiao reservoir breaching process in this study considering the erosion of different dam materials and the failure of clay core. Based on the calculated results, the following conclusions can be drawn: The clay core dam can be assumed as a composite dam with noncohesive and cohesive materials; a shear failure formula is adopted to calculate the time and height of failure clay core; for the dam with relatively small dam height and large reservoir storage, base erosion should be considered if the foundation is erodible. Based on the contrast of calculated and measured results, the proposed model can reproduce good results, and can be utilized for the breaching process of clay core dam due to overtopping failure.

6. ACKNOWLEDGMENT

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