Analysis of Sand Flow Evolution in Tailing Dam Failure

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Abstract

This paper presents study on sand flow evolution during the failures of tailing dam by using unsteady two-dimensional planar equation averaged on depth. The depth and velocity field of sand flow within the area affected by tailing dam failure are obtained by applying nonlinear iteration and discretized analysis of tailing flow model. In addition, numerical analysis performed by using FLUENT further provides detailed characteristics of tailing distribution and the velocity variation during tailing failure.

Keywords

Safety Engineering; Dam-Break; Sand Flow; Tailings Dam; Environmental Safety; Fluent

Analytical Method on the Evolution of Tailing Flow

To study the failure models of tailing dam, the tailing dam can be considered as homogeneous material and the failure can be divided into two stages – Initial failure when horizontal breach appears at the top of the dam; and following failure when the failure groove occurs along the downward slip of the dam. At the first stage the flow at the horizontal breach can be assumed as weir flow with wide top, which develops with the evolution of dam failure. As it develops the cross section of the flow at the groove of breach can be assumed as trapezoidal during the second stage. It is actually a wedge slipping structure resulted from the continuous scouring of the upstream flow. The duration of this evolution varies from a few seconds to more than ten seconds [1], depending on the internal structure of the dam. Failure of tailing dam often occurs under a particular condition with great external change, e.g. massive rainfall, earthquake or severe damage of the dam slope associated with plenty of water flow. Tailing flow has strong mobility, which differs from ordinary river sands or muds. It accelerates dramatically after dam failure and forms an impact area of great destruction [2].

Simulations on the Failure of Tailing Dam

The flow pattern of tailing dam failure is consistent with that of slope sliding/debris flow [3]. Therefore, the tailing flow can be considered as debris flow, and the calculation on the tailing flow after dam failure can be performed by the method for slope sliding/debris flow [4, 5], in which the dynamic equation and continuity equation are used to represent the motion of tailing flow [6, 7]. It is hence assumed in the calculation of tailing flow after the dam failure that: the tailing flow is a continuous media with homogeneous properties in every direction; only the deformation caused by deviation stress tensor is considered [2], with other deformation being neglected; the tailing flow follows the Bingham flow [1].

Mathematic Model of Tailing Dam Failure

Fundamental Equation for the Tailing Flow of Tailing Dam

Given the above assumptions, the unsteady planar two-dimensional equation averaged in depth can be established to describe the evolution of tailing flow [3]
where \( z \) defines the elevation of tailing flow surface; \( h \) is the depth of tailing flow; \( u \) and \( v \) denote the flow velocities along \( x \) and \( y \) directions, respectively; \( g \) is the acceleration of gravity and \( \rho \) is the density of tailing; \( c \) is the Chezy coefficient; \( \tau_{xx}, \tau_{xy} \) and \( \tau_{yy} \) are the average planar deviator stresses along the \( z \) direction; \( \tau_r \) is the rheological limit.

**Constitutive Modeling for Calculation of Tailing Flow**

The rheological equation is built assuming that the tailing flow follows the Bingham flow

\[
\varepsilon = \frac{\sigma}{E} \quad (\sigma < \sigma_s) \tag{4}
\]

\[
\varepsilon = \frac{\sigma - \sigma_s}{\eta} \quad (\sigma \geq \sigma_s) \tag{5}
\]

where \( \varepsilon \) is the strain; \( \sigma \) is the stress; \( \sigma_s \) is the stress at yield; \( E \) is the Young’s modulus and \( \mu \) is the viscous coefficient.

If only the elasto-viscous behavior of tailing is considered during the calculation of tailing flow after breaching, Equation (4) and (5) can be integrated along depth as

\[
\frac{\mu}{G} \left( \frac{\partial s_{ij}}{\partial t} - s_{ij} \frac{\partial h}{\partial t} \right) + h s_{ij} = 2 \mu \left( \frac{\partial e_{ij}}{\partial t} - e_{ij} \frac{\partial h}{\partial t} \right) \quad (i, j = x, y) \tag{6}
\]

where \( s_{ij} \) is the deviatoric stress tensor averaged over the depth; \( e_{ij} \) is the deviatoric strain tensor averaged over the depth; \( s_{ij} \) is the partial stress component on the free surface; \( s_{ij} \) is the strain component at the free surface of tailing flow; \( G \) is the shear modulus. If the following is assumed:

\[
R_{ij} = 2 \mu \left( \frac{\partial e_{ij}}{\partial t} - e_{ij} \frac{\partial h}{\partial t} \right) + \frac{\mu}{G} s_{ij} \frac{\partial h}{\partial t} \tag{7}
\]

then it is possible to obtain:

\[
\frac{\mu}{G} \frac{\partial s_{ij}}{\partial t} + h s_{ij} = R_{ij} \tag{8}
\]

Integrating the above equation over time, one obtains:

\[
- s_{ij} = (s_{ij} - \frac{R_{ij}}{h}) \frac{e^{-\mu t}}{\mu} + \frac{R_{ij}}{h} \tag{9}
\]

**Boundary Condition for the Calculation of Tailing Flow at the Tailing Breach**

Firstly a thin layer of tailing sand is assumed to exist within the influence zone of downstream dam breach. Within this layer the sand quantity can be ignored compared with the total tailing sand. The initial velocity components \( u \) and \( v \) can be assumed to be 0. Open boundary condition is applied to the breach edge, where the flow hydrograph is considered as the boundary and the flow velocity normal to the boundary is zero.

**Discrete Model on the Failure of Tailing Dam**

Equation (9) is a nonlinear expression of partial differential equations and the calculation method is complicated.
The baseline equation to calculate the tailing flow can be discretized to facilitate the numerical calculation. The discretization proposed by Chen Qingsheng [7] is adopted to establish the discrete model to simulate the tailing flow during dam failure.

$$\frac{Z_{i,j}^{n+1} - Z_{i,j}^n}{\Delta t} + \frac{h_{i,j}^n (u_{i,j}^{n+1} - u_{i,j+1}^n)}{\Delta x} + \frac{h_{i,j}^n (v_{i,j}^{n+1} - v_{i,j-1}^n)}{\Delta y} = 0$$  \hspace{1cm} (10)

$$\frac{u_{i,j}^{n+1} - u_{i,j}^n}{\Delta t} + \frac{u_{i,j}^{n+1} - u_{i+1,j}^n}{2\Delta x} + \frac{v_{i,j}^{n+1} - v_{i,j-1}^n}{2\Delta y} + g \frac{z_{i,j}^{n+1} - z_{i,j}^n}{\Delta x} = \frac{1}{\rho h_{i,j}^{n+1}} \left( \frac{h_{i+1,j}^{n+1} - h_{i,j}^{n+1}}{\Delta x} + \frac{h_{i,j+1}^{n+1} - h_{i,j}^{n+1}}{\Delta y} \right)$$  \hspace{1cm} (11)

$$\frac{v_{i,j}^{n+1} - v_{i,j}^n}{\Delta t} + \frac{v_{i,j}^{n+1} - v_{i-1,j}^n}{2\Delta x} + \frac{v_{i,j}^{n+1} - v_{i,j-1}^n}{2\Delta y} + g \frac{z_{i,j}^{n+1} - z_{i,j}^n}{\Delta y} = \frac{1}{\rho h_{i,j}^{n+1}} \left( \frac{h_{i+1,j}^{n+1} - h_{i,j}^{n+1}}{\Delta x} + \frac{h_{i,j+1}^{n+1} - h_{i,j}^{n+1}}{\Delta y} \right)$$  \hspace{1cm} (12)

where

$$\bar{h}_{i,j} = \frac{h_{i,j}^n + h_{i+1,j}^n}{2}, \quad \bar{h}_{i,j} = \frac{h_{i,j}^n + h_{i,j+1}^n}{2}, \quad \bar{u}_{i,j} = \frac{u_{i,j}^n + u_{i-1,j}^n + u_{i,j+1}^n + u_{i,j+1}^n}{4},$$

$$\bar{v}_{i,j} = \frac{v_{i,j}^n + v_{i,j-1}^n + v_{i+1,j}^n + v_{i+1,j-1}^n}{4}, \quad \bar{c}_{i,j} = \frac{c_{i,j} + c_{i+1,j}}{2}, \quad \bar{c}_{i,j} = \frac{c_{i,j} + c_{i,j+1}}{2}.$$

When the two-dimensional simulation is performed on the tailing flow at breach failure, it is assumed $s_{yz} = S_y$, $e_{yz} = e_y$ and the nonlinear iteration continues till the desired accuracy is reached. Finally the depth and velocity field of tailing flow within the influence zone of dam breach are acquired.

**Evolution Analyses on Two-Dimensional Tailing Flow Based on Numerical Simulations**

The evolution of dam breach is complex and influenced/restricted by many factors. In this paper many parameters are studied with respect to preliminary 2D simulation/analysis on the dam failure.

For complex fluid analysis, the Finite Volume Method software Fluent is commonly used in the recent years in terms of flow of fluid [8], heat transfer process, combustion and pollution, which applies finite volume method for mesh generation and establishes discretized equations [2, 7]. Fluent is thus adopted in this paper to analyze the evolution of tailing breach.

**Generals of a Tailing Dam**

The tailing dam is in hilly U shape with slope angle of 10–15°at the valley and 25–45°at the crest. About 20 households scatter within the downstream 5km, with farmland and activities of agriculture and livestock in some area of the region. The total volume of this tailing dam is 896000m³, with a height of 49m (Class 4). The
beneficiation method for this dam is mainly magnetic separation. No chemical substance is found in the tailing, but certain amount of heavy metal element exists. After the tailing dam failure it can be imagined that there would be major impact on the local land, water as well as ecology system.

**Generalized Model for the Tailing Dam**

In the model, the dam has a height of 49m, a length of 400m and a slope of 1:4. The tailing density is 17.5kN/m³, dynamic viscosity is 500Pa.s, height coefficient on friction at downstream is 0.013, friction coefficient is 0.7, unit area of mesh is 3 and the total size is 150×5000m. Results present the movement of tailing at 15s, 30s, 60s, 90s, 120s, and 150s, respectively, with pressure unit of pa and velocity unit of m/s. Critical condition of rainstorm is considered to assume the complete saturation of tailing dam in which all tailings breach out. The generalized dam model is divided into two zones, where the red color represents air. The left boundary is the exit of pressure and right boundary is fixed.

**Study on Distribution of the Tailing Flow after Failure**

The VOF model is adopted in the calculation. Calculated by Fluent and post-procesed by tecplot, the distribution of tailing flow head from 15s to 150s is obtained after dam breach. Figure 1 and 2 present this distribution at 30s and 150s. From the figures the deposition of tailing flow at a certain time section can be analyzed. For example, at coordinate of 4300 (100m away from the dam origin) after 15s, the thickness is 11.9m; at coordinate of 4000 (400m away from the dam origin) after 30s, the thickness is 8.5m; at coordinate of 2800 (1600m away from the dam origin) after 90s, the thickness is 4.7m and at coordinate of 1900 (2500m away from the dam origin) after 150s, the thickness is 2.1m.

At the time of 120-150s, the velocity of tailing flow increases to 14.5m/s whereas at 150s the head of tailing has moved 2720m in total, to the coordinate of 1680. At the past position of 1900 the thickness of deposited tailing is 2.1m. The above position is 2500m far from the dam, which indicates strong destruction of flow discharge.

**Study on the Velocity Distribution of Tailing Flow Evolution**

The distribution of velocity as well as velocity vector is captured at 15s, 30s, 60s, 90s, 120s and 150s based on software analysis. The distribution of velocity magnitude and vector at 30s is presented in Figure 3.
From the distribution of velocity and its vector, it can be noted that during the discharge of tailing, the velocity of tailing reaches the maximum at the head in the beginning (15s) and it contains upward velocity component. On the rapid movement of tailing till about 90s, the velocity at the head is almost the same as that in the middle of flow, but smaller velocity is obtained at the rear zone. At the time of 150s the tailing flow is powered by the middle part with the velocity at the head smaller than that in the middle. As illustrated in Figure 4 for the distribution of tailing during evolution, the velocity of tailing flow rockets before 30s but begins to decrease at 30s. The tailing rear moves 2720m in total within 15s with the average discharge velocity of 18.13m/s. The maximum velocity is observed between 15s and 30s with the average discharge velocity of 25.33m/s. During the evolution process the tailing sand exhibits aggressive advancement, very short duration and devastating impact.

**FIGURE 3. DISTRIBUTION AND VELOCITY VECTOR OF TAILING AT 30S.**

**FIGURE 4. MEAN VELOCITY DISTRIBUTION OF TAILING AT EACH INTERVAL DURING EVOLUTION.**

**Conclusions**

Through the discretization of fundamental equations describing the tailing flow at dam breach, the discrete element Fluent is adopted to obtain the characteristics of parameters during evolution of tailing flow at breach. This method plays a significant role to study the damage and influence caused by tailing flow. The analysis provides both the distribution and the velocity distribution of tailing sand at different time and locations. The results show that the velocity reaches the maximum value between 15s and 30s after the breach with the maximum destruction; after 30s, the velocity of tailing flow decreases dramatically and at 90s, velocity at the head is almost the same as that in the middle of flow. The velocity at the head of flow is smaller than that in the middle at the 150s.

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