Potential Risk Analysis of Tailings Dam under Preloading Condition and Its Countermeasures

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Abstract. It is very important for mine production safety to ensure the stability of the tailings dam. Taking a flatland tailings pond as the background, a three-dimensional computational model was built based on a tailings dam under mullock heap preloading condition. Considering the current operating water level conditions, a liquid-solid coupling analysis of the model was conducted. The deformation characteristics of the tailings dam were revealed during successive preloading at the front of the dam. The safety factor and the potential slide face of the tailings dam were calculated under different conditions using the strength reduction method. The results show that the tailings dam in its current condition is basically stable, but if the mullock heap continues to be heightened, the tailings dam will become unstable. Therefore, in order to limit the height of the mullock heap, establishing a monitor and early warning mechanism are put forward to ensure mine production safety.

Keywords: *tailings dam; mullock heap; liquid-solid coupling; strength reduction method; safety factor.*

1 Introduction

The tailings pond is a necessary facility for maintaining normal production of a mine as a place for stockpiling tailings. On the other hand, the tailings dam is a major danger for metal and nonmetal mines, because dam failure may occur. A possible tailings accident can cause not only great losses and endanger the lives and properties of downstream residents but also lead to serious environmental pollution.

Many scholars have studied the stability of tailings ponds and dam failure disasters. R.A. Shakesby, *et al.* have studied the tailings dam accident at the Arcturus gold mine in Zimbabwe and concluded that the dam failure resulted from the poor seepage condition of the dam's foundation, too steep a dam slope

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and the tailings being in a saturated state under heavy rain [1]. After investigating tailings dam failures in America, C. Strachan holds that dam failures resulted from flood overtopping, static or dynamic instability, seepage, internal corrosion and poor foundation conditions [2]. D. Chakraborty, *et al.* investigated the behavior of an earthen tailings dam under static and seismic conditions and found that dam deformation is affected seriously by seismic action and that the underlying input acceleration of the tailings dam had an amplifying effect along the height of dam [3]. P. Sjödahl, *et al.* conducted a safety evaluation of the Enemossen tailings dam in southern Sweden using resistivity measurements [4]. D. Brett, *et al.* have completed the geotechnical design of a main creek tailings dam applying the upstream construction method [5].

Q. Li, *et al.* summarized two instability models based on the combination of a liquid-solid coupling method with a strength reduction method. One was global instability and the other was local instability mostly caused by a too shallow saturation line in the tailings dams [6,7]. D.Q. Chen *et al.* provided a comprehensive method to evaluate tailings dam stability through numerical calculation of the seepage stability, static stability and dynamic stability of a specific project [8]. G.Z. Yin *et al.* studied the regularity of the saturation lines' change under flooding and normal conditions, when the dam was heaped up to about two-thirds of the total height of 120 m [9]. M.J. Hu, *et al.* analyzed the anti-slide stability of an upstream tailing by changing the dam's height, the saturation line conditions and the drainage system operating conditions [10]. G.Z. Li, *et al.* analyzed the stability of a tailings dam with the Sweden method and the Bishop method and gave the interrelated parameters of the stability and credibility of the dam structure when its level was raised to 510-520 m [11]. J.D. Lou *et al.* calculated the effect of heightening a dam on the stress-strain isoline through simulation using the finite element method (FEM) and evaluated the dam's stability with the residual thrust method [12,13], etc.

2 Engineering Overview

We take the flatland tailings pond of the Sanshan Island gold mine, Shangdong Province, China, shown in Figure 1, as an example. It covers an area of about 0.22 km^2, a catchment area of about 0.21 km^2. The ground level is about 3.1-4.2 m and the reservoir elevation is about 3.5-20.7 m. The starter dam consists of roller compacted sand with a height of 11.0 m, top width of 3.0 m and outer slope ratio of 1:1.8-1:2.5.

The waste rock has been heaped up from 2010 at the northwest corner of the tailings dam. Its accumulation level is up to 38.5 m, which is 11 meters higher than that of the tailings stacking dam (status elevation 27.5 m). The plane shape of the waste rock heap is approximately rectangular, with an east-west length of 260 m and a north-south length of 110 m, covering an area of about 1.89 × 104 m^2 and occupying a volume of 36.67 × 104 m^3. About 50 m wide at the south side of the mullock heap, it weighs on the north slope of the dam. The mullock heap slide is unaffected until a natural repose slope ratio of 1.0:1.1-1.0:3.0 and no obvious collapse or crack was found during the site investigation. Figure 1 shows the plan of the tailings pond and mullock heap.

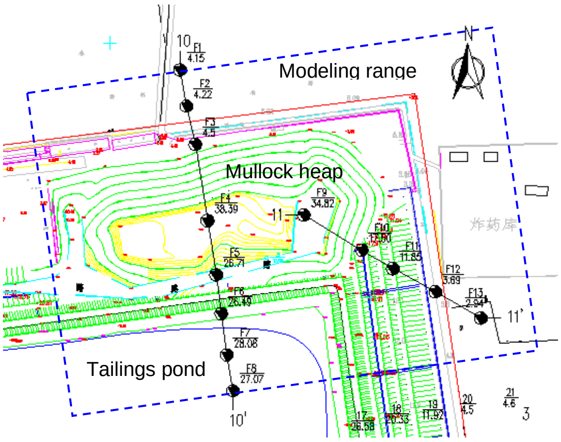

Figure 1 The plan of the tailings pond and mullock heap.

According to the drilling survey result, the stratum is divided into three layers, from top to bottom: mullock material, tailings material and the natural formation. The mullock heap mainly consists of gravel with silt. The tailings fill dam mainly consists of tailings silt and silty clay. The original ground is composed of medium coarse sand of alluvial-diluvial and marine deposit genesis and alluvial-diluvial silty clay.

3 3D Model and Simulation Analysis Scheme

3.1 Building the Computational Model

In view of the technical difficulties of $FLAC^{3D}$ (Fast Lagrangian Analysis of Continua) for complex 3D engineering modeling, the finite element software MIDAS/GTS from South Korea was adopted for geometric modeling of the complex geologic body and mesh generation, followed by model data transformation from MIDAS/GTS to $FLAC^{3D}$ to make up the pre-processing shortcomings of $FLAC^{3D}$ and give full play to its powerful calculating function.

Although the element shape of MIDAS/GTS is basically the same as that of $FLAC^{3D}$, the node numbering rules and node order are different, therefore, the element and node data exported from MIDAS/GTS have to be rearranged according to a FLAC^{3D} recognizable format and then be imported, thus realizing a data transformation between the two software applications, which can be done by programming. The entire modeling process is shown in Figure 2.

The tailings dam 3D numerical model (Figure 3) was built following the aforementioned procedure. A system of coordinate axes was defined with the origin at the silty clay layer 34 m beneath the natural ground, with the *z*-axis pointing upward. The model was approximately 280 m long, 250 m wide and 38.5 m high in the *x*-, *y*-, and *z*-axis, respectively. The present height of the waste rock was 38.5 m and its future height 42.0 m.

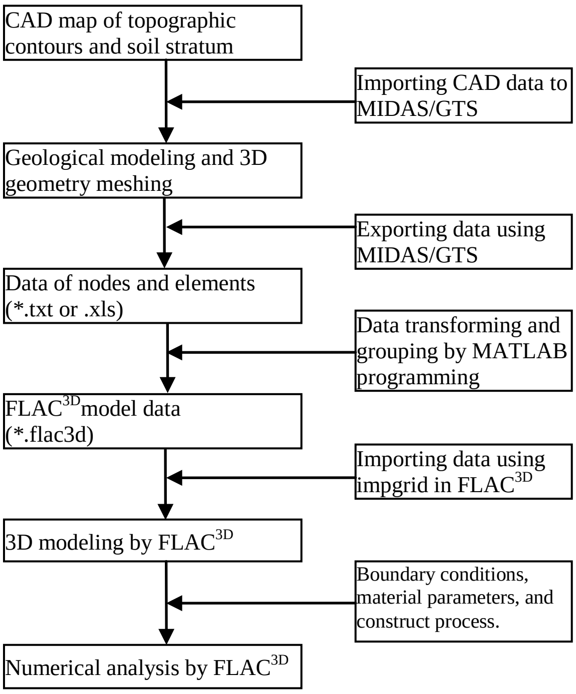

Figure 2 Flow chart of three-dimensional modeling process.

The horizontal displacement of the four lateral boundaries of the model was restricted, the bottom was fixed and the top was free. Only the geomaterial dead weight was taken into account to obtain the initial stress field. The material of the model was supposed to meet the Mohr-Coulomb strength criterion and the physics and mechanics parameters were selected as listed in Table 1 according to the field test and the laboratory test.

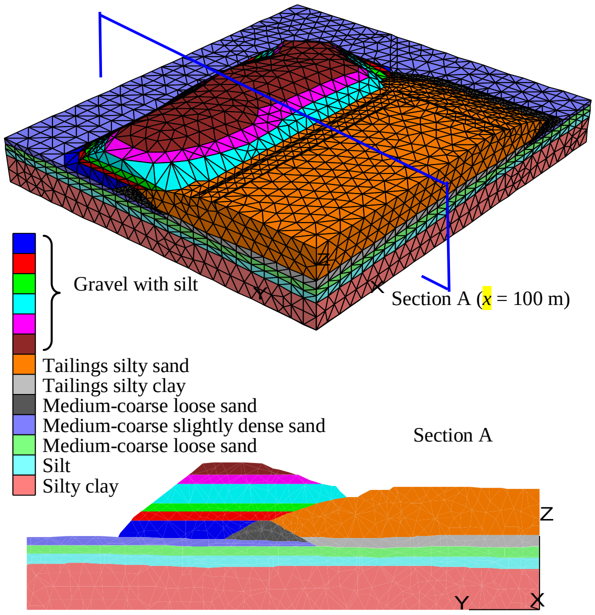

Figure 3 3D model mesh and its material sets.

Table 1 Physics and mechanics parameter of the model.

Name	**Density (kg/m^3)**	**Elasticity modulus (GPa)**	**Poisson ratio**	**Cohesion (kPa)**	**Friction angle (°)**	**Permeability coefficient ($cm \cdot s^{-1}$)**
Gravel with silt	2250	50	0.32	1	35	1.34×10^{-1}
Tailings silty sand	1710	15	0.40	3	25	2.93×10^{-3}
Tailings silty clay	1910	8	0.35	19	8	2.30×10^{-6}
Medium-coarse loose sand	1950	70	0.30	3	30	1.70×10^{-2}
Medium-coarse slightly dense sand	1960	75	0.30	3	32	3.20×10^{-2}
Medium-coarse loose sand	1870	63	0.30	3	29	2.80×10^{-3}
Silt	2190	47	0.32	30	20	1.20×10^{-4}
Silty clay	2030	80	0.30	35	15	1.50×10^{-6}
Water	1000					

3.2 Liquid-Solid Coupling in FLAC^{3D}

The fluid-solid coupling behavior involves two mechanical effects in FLAC^{3D}. First, changes in pore pressure cause changes in effective stress of the solid. Second, the fluid in a zone reacts to mechanical volume changes by a change in pore pressure.

The variables of fluid flow through porous media such as pore pressure, saturation and the specific discharge are related through the fluid mass-balance equation, Darcy's law for fluid transport, a constitutive equation specifying the fluid response to changes in pore pressure, saturation, volumetric strains and an equation of state relating pore pressure to saturation in the unsaturated range. Assuming the volumetric strains are known, substitution of the mass balance equation into the fluid constitutive relation, using Darcy's law, yields a differential equation in terms of pore pressure and saturation that may be solved for particular geometries, properties, boundary and initial conditions.

In summary, possible causes of tailings dam failure include flood overtopping, slope instability, seepage failure, structural damage and seismic liquefaction, etc. In general, the stability of a tailings dam being influenced by the seepage field cannot be ignored. The current study is mainly based on the assumption of two-dimensional plane strain. There is little literature on three-dimensional (3D) stability of the tailings seepage and deformation, so a 3D numerical model was built based on a flatland tailings pond project, to conduct a liquid-solid coupling analysis of the potential risk due to successive preloading at the front of the dam. Some engineering countermeasures will be put forward corresponding to the evaluation results.

3.3 Simulation Analysis Schemes

The numerical simulation consisted of four steps as follows:

Step 1: The initial seepage field and initial stress field were calculated under the current operating water level of 27.0 m and then the displacements were reset to zero.

Step 2: The heap process was divided into six steps up to the present level of 38.5 m to analyze the deformation characteristics of the tailings dam under the current conditions.

Step 3: The heap height was increased with an additional accumulation to a height of 42.0 m and the deformation characteristics analysis of the tailings dam was repeated.

Step 4: A stability evaluation and potential risk analysis of the tailings dam were carried out by using the liquid-solid coupling method considering different preloading conditions and corresponding safety factors were formulated.

4 Liquid-Solid Coupling Analysis of Tailings Dam

4.1 Pore Pressure Distribution of the Flow Field under Current Operating Level

In order to facilitate the analysis, a vertical cross section at *x* = 100 m (section A) was defined, as shown in Figure 2. All of the results below occurred in section A under the current operating water level of 27.0 m.

It can be seen from the pore pressure distribution (Figure 4) under the condition of the current operating water level that the stable seepage line in the tailings dam extends from the embankment to the outer toe of the slope of the mullock heap, where failure occurs more easily due to the seepage of groundwater.

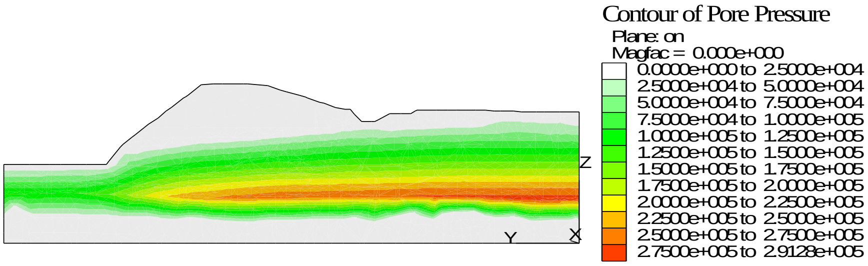

Figure 4 Pore pressure distribution under the current water level.

4.2 Deformation Characteristics of the Tailings Dam under Gradual Accumulation

The calculation results of the displacement fields are displayed below, where Figures 5 and 6 correspond to the current elevation of the mullock heap (38.5 m), while Figures 7 and 8 correspond to the additional heaped elevation (42.0 m). By comparative analysis it can be seen that:

Apart from its consolidation deformation owing to self-gravity under gradual accumulation of the mullock heap, the outside ground surface, starter dam and outer slope of the tailings fill dam are loaded and crushed with different deformation characteristics as a result of their different stiffnesses. The outer slope toe of the mullock heap consists mainly of surface settlement and lateral uplift. The tailings dam deforms inward under pressure with a certain lateral deformation that results in a little uplift of the tailings silty sand. From the viewpoint of magnitude, the horizontal displacement of 180 mm toward the inner tailings dam is close to the 179 mm in the opposite direction in Figures 5 and 6, but the horizontal displacement of 199 mm toward the inner tailings dam is smaller than the 227 mm in the opposite direction in Figures 7 and 8. The aforementioned deformations developed significantly after the height of the mullock heap was increased.

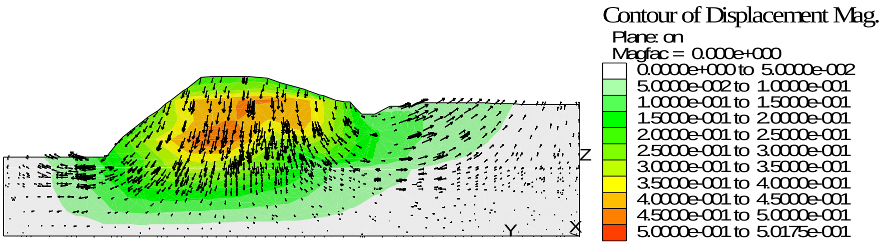

Figure 5 Displacement field and arrow under the current height.

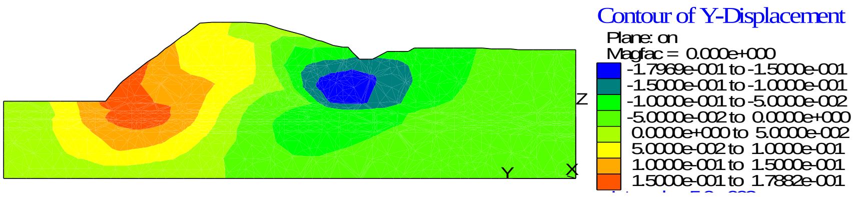

Figure 6 Horizontal displacement field under the current height.

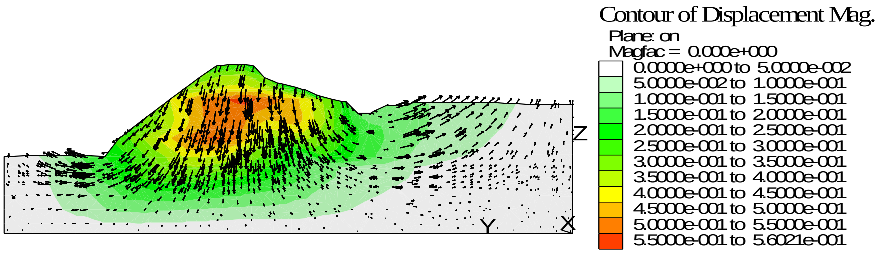

Figure 7 Displacement field and arrow under the future height.

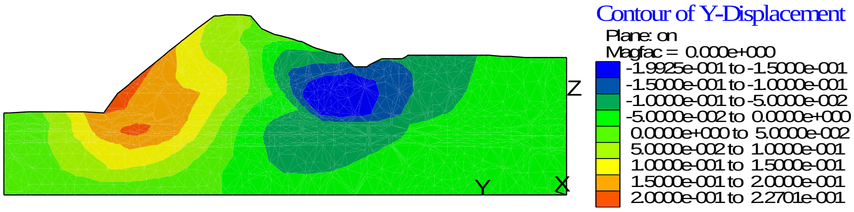

Figure 8 Horizontal displacement field under the future height.

The results suggest three potential failure modes of the tailings dam under preloading: (1) the compressive shear zone in the outside ground is likely to induce a sliding failure through the outer slope toe of the tailings dam in case additional loading is continued; (2) local compression and shear failure could appear during the deformation process of the tailings dam under gradual preloading; (3) an uplift failure may occur in the tailings embankment as the load increases when the mullock heap is heightened.

4.3 Safety Risk Analysis of Tailings Dam under Gradual Accumulation

According to China technical codes, the safety factor of the tailings dam in this example project should be not less than 1.25 under normal operating conditions. The internal shear strength reduction method of FLAC^{3D} was adopted to calculate the safety factor of the tailings dam for different heap heights and to determine the potential slip surface position. The maximum shear strain increment of the tailings dam is 15.2 under the present heap height 38.5 m (Figure 9), which would increase to 24.7 when the mullock heap is heightened to 42.0 m (Figure 10), and the potential slip surface would change from 1 (Figure 9) to 2 (Figure 10). The safety factor (FoS) of the tailings dam is 1.28 under the present heap height 38.5 m (Figure 9), which would reduce to 1.23 when the mullock heap is heightened to 42.0 m (Figure 10). This means that there is a lack of safety reserve and the heap height should not be increased.

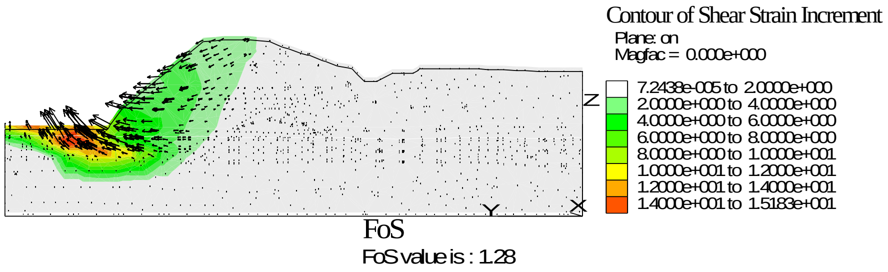

Figure 9 Potential slip surface and safety factor under the current height.

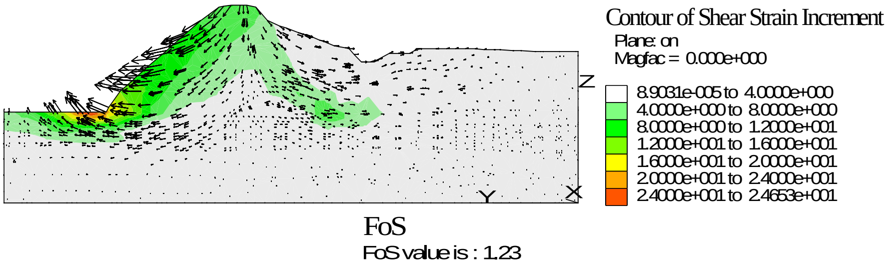

Figure 10 Potential slip surface and safety factor under future height.

5 Conclusion

It is concluded from the liquid-solid coupling analysis that there are three potential failure modes of the tailings dam under preloading: (1) the compressive shear zone in the outside ground is likely to induce a sliding failure through the outer slope toe of the tailings dam; (2) local compression and shear failure could appear during the deformation process of the tailings dam under gradual preloading; (3) an uplift failure may occur in the tailings embankment when the mullock heap is heightened. Under the present conditions, the tailings dam meets the safety requirements, whereas it does not in the event of additional heaping.

According to the above results, the following engineering countermeasures are put forward: the height of the present heap must be cut to satisfy the stability requirements under the condition of rain infiltration. A sound monitoring and regular inspection should be established to ensure the safety of the tailings pond operation. Engineering practice has shown that these measures achieve good results.

Acknowledgments

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