Paper No. 125

ISMS 2016

Liquid-solid coupling analysis of tailings dam under complex engineering conditions

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ABSTRACT
The tailings pond, a place for stockpiling tailings, is a necessary facility for maintaining normal production of a mine. On the other hand, the tailings dam is a major danger for metal and non-metal mines, because dam failure may occur. The present study takes the flat land tailings pond of the Sanshan Island gold mine, Shangdong Province, China, as an example. The tailings dam 3D numerical model was built using MIDAS/GTS and FLAC^{3D} techniques. The safety factor and the potential slide face of the tailings dam were calculated under different conditions using the strength reduction method. It is concluded from the liquid-solid coupling analysis that there are three potential failure modes of the tailings dam under preloading. Under the present conditions, the tailings dam meets the safety requirements, however, it does not in the event of additional heaping. The height of the present heap must be cut to satisfy the stability requirements under the condition of rain infiltration.

1. INTRODUCTION

The tailings pond is a necessary facility for maintaining the normal production of a mine, and as a place for stockpiling tailings. On the other hand, the tailings dam is a major danger for metal and non-metal mines, as dam failure may occur. In the case of a possible tailings accident, it will cause not only great losses and harm the safety of life and property to the residents downstream of the mine, but also serious environmental pollution.

Many scholars have studied the stability of the tailings pond and dam failure disasters. Shakesby and Richard (1991) studied the tailings dam accident in Arcturus gold mine in Zimbabwe. They hypothesized that the dam failure resulted from the poor seepage conditions of the dam foundation, as the dam slop was too steep and the tailings were saturated under heavy rain. Through investigating the tailings dam failure in America, Strachan (2001) held that the dam failure was a result of flood overtopping, static or dynamic instability, seepage, internal corrosion and poor foundation conditions. Chakraborty and Choudhury (2009) investigated the behavior of tailings earthen dam under static and seismic conditions, and found that the dam deformation was affected seriously by seismic action. Additionally, the underlying input acceleration of tailings dam had an amplification effect along the height of dam. Bussière et al. (2003) modeled the flow field characteristic for exposed and covered tailings dams using the finite element method (FEM). Valenzuela and Barrera (2003) analyzed the seismic stability of the dam up to a height of 195 m by the limit equilibrium method in Los Quillayes copper mine in Chile, indicating that a dam height of 195 m was feasible.

Li et al. (2012) summarized two instability models based on the combination of the liquid-solid coupling method with the strength reduction method. One method concerned global instability and the other local instability, which is mostly caused by the too shallow saturation line in the tailing dams. Chen et al. (2008) provided a comprehensive method to evaluate the tailings dam stability with numerical calculation of the seepage stability, static stability and dynamic stability of a specific project. Yin et al. (2010) studied the change regularity of the saturation lines during normal and flood conditions, when the dam had been heaped to about two thirds of the total height of 120 m. Hu et al. (2004) analyzed the anti-slide stability of the upstream tailing by changing the dam height, saturation line conditions and the drainage system operating conditions. Li et al. (2005) analyzed the stability of a tailings dam using the Sweden method and Bishop method, giving the interrelated parameter of the stability and the credibility of the dam structure when its level was raised to 510-520 m. Lou et al. (2005) calculated the stress-strain isoline of the higher dam in the future by using FEM, and evaluated the dam's stability with the residual thrust method.

The main causes of tailings dam failure include flood overtopping, slope stability, seepage failure, structural damage and seismic liquefaction. The influence of the seepage field on the stability of the tailings dam cannot be ignored. The current study is

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mainly based on a two-dimensional plane strain assumption. In order to correct the lack of analysis of three-dimensional (3D) stability of the tailings seepage and deformation, a 3D numerical model was built based on a flatland tailings pond project, to conduct the liquid-solid coupling analysis of the potential risk due to successive preloading in front of the dam. Afterwards, engineering countermeasures were put forward according to the evaluated results.

2. ENGINEERING OVERVIEW

As shown in Figure 1, taking the flatland tailings pond in China as an example, the pond covered an area of about 0.22 km^2, and had a catchment area of about 0.21 km^2. The ground level was about 3.1 m - 4.2 m, and the reservoir elevation was about 3.5 m - 20.7 m. The starter dam consisted 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. Figure 1 shows the plan of the tailings pond and the mullock heap.

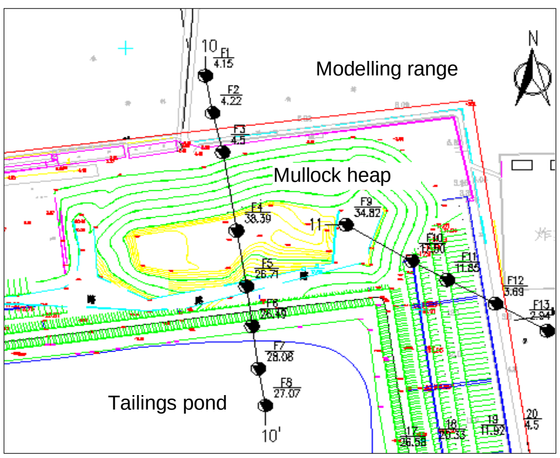


Figure 1: Schematic of borehole layout and the calculation range.

The waste rock heaped up from 2010 in the northwest corner of the tailings dam, with an accumulation level up to 38.5 m, a height 11 meters higher than that of the tailings stacking dam (status elevation 27.5 m). The plane shape of the waste rock heap was approximately rectangular with an east-west length of 260 m, and a 110 m length from north to south, covering an area of about 1.89 × 10^4 m^2 and occupying a volume of 36.67 × 10^4 m^3. The mullock heap was about 50 m wide in the south, and it weighed on the north slope of the dam. The mullock heap slide was 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.

According to the survey results of drilling, the stratum was divided into three layers from top to bottom: mullock material, tailings material and the natural formation. The mullock heap was mainly gravel with silt. Tailings fill dam were mainly tailings silt and silty clay. The original ground was 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} for complex 3D engineering modelling, the finite element software MIDAS/GTS of South Korea was adopted for geometric modeling of complex geologic body and mesh generation, followed by model data transformation from MIDAS/GTS to FLAC^{3D}, to make up for 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 should be rearranged according to the FLAC^{3D} recognizable format and then be imported, thus realizing data transformation between the two programs. This can be achieved by programming. The entire modeling process is shown in Figure 2.

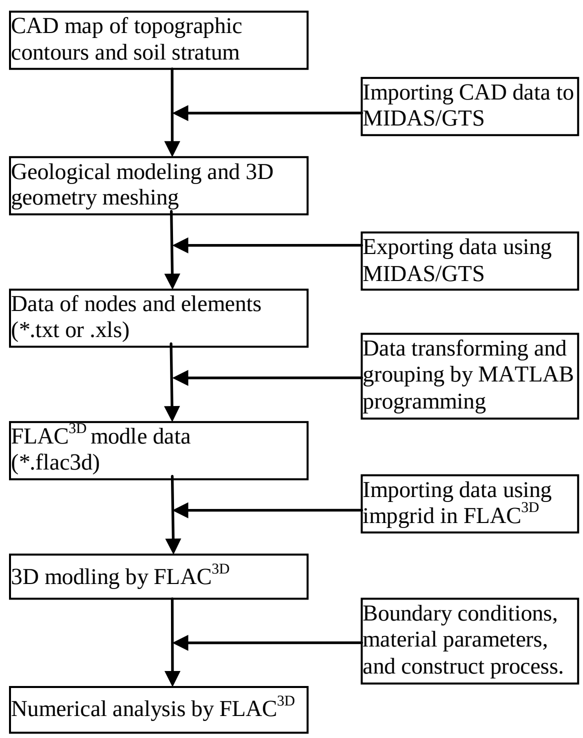


Figure 2: Flow chart of three-dimension modeling process.

The tailings dam 3D numerical model (Figure 3) was built following the aforementioned procedure, corresponding to the scope of the blue dashed line in Figure 1. A system of coordinate axes was defined with the origin at the silty clay layer beneath the natural ground of 34 m, 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, with a future height of up to 42.0 m.

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

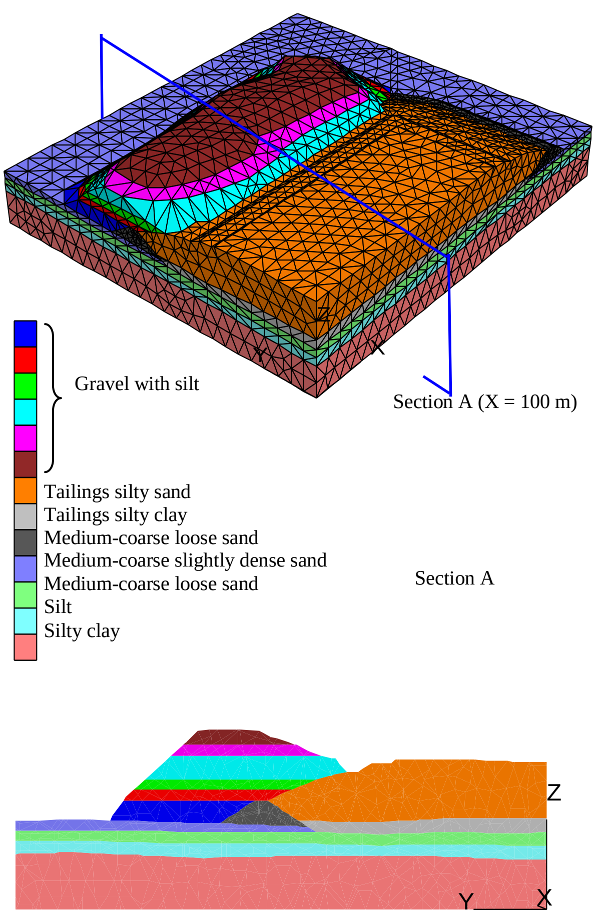


Figure 3: 3D model mesh and its material sets.

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

The fluid-solid coupling behaviour 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. 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 currently 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 are 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 42.0 m high, and the deformation characteristics analysis of the tailings dam was repeated.

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

Table 1: Physics and mechanics parameter of the model.

No.	Name	Density /kg/m^3	Elasticity modulus /GPa	Poisson ratio	Cohesion /kPa	Friction angle / °	Permeability coefficient /cm·s^{-1}
1	Gravel with silt	2250	50	0.32	1	35	0.134
2	Tailings silty sand	1710	15	0.40	3	25	2.93×10^{-3}
3	Tailings silty clay	1910	8	0.35	19	8	2.3×10^{-6}
4	Medium-coarse loose sand	1950	70	0.30	3	30	1.7×10^{-2}
5	Medium-coarse slightly dense sand	1960	75	0.30	3	32	3.2×10^{-2}
6	Medium-coarse loose sand	1870	63	0.30	3	29	2.8×10^{-3}
7	Silt	2190	47	0.32	30	20	1.2×10^{-4}
8	Silty clay	2030	80	0.30	35	15	1.5×10^{-6}

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 are shown 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 tailings dam extended from the embankment to the outer toe of the slope of the mullock heap, where failure occurred more easily due to the seepage of groundwater.

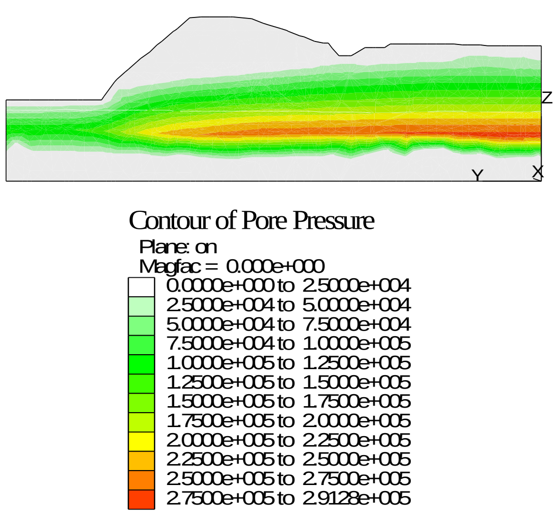


Figure 4: Pore pressure distribution under the current water level.

4.2 Deformation characteristics of the tailings dam under gradual accumulation

The calculation results of displacement fields are displayed below, with Figures 5 and 6 corresponding to the current elevation of the mullock heap (38.5 m) and Figures 7 and 8 corresponding 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 accumulations of the mullock heap, the outside ground surface, starter dam and outer slope of tailings fill dam are loaded and crushed with different deformation characteristics as a result of their different stiffnesses. The outer slope toe of mullock heap is mainly surface settlement and lateral uplift. The tailings dam deforms inward under pressure with a certain lateral deformation that results in a little uplift of tailings silty sand. From the view of magnitude, the horizontal displacements toward inner tailings dam are close to that in the opposite direction. The aforementioned deformations developed significantly with the increasing height of the mullock heap.

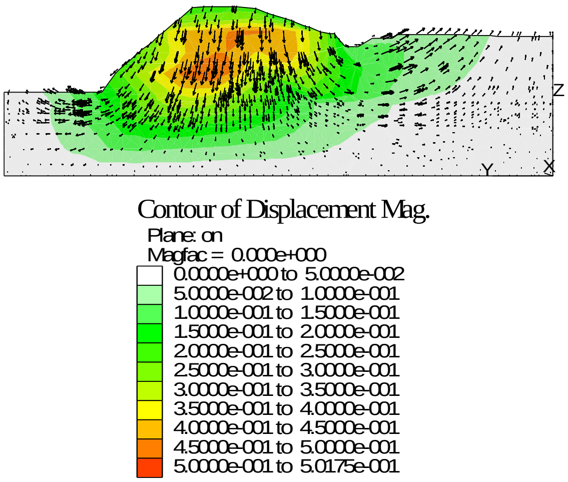


Figure 5: Displacement field and arrow under the current height.

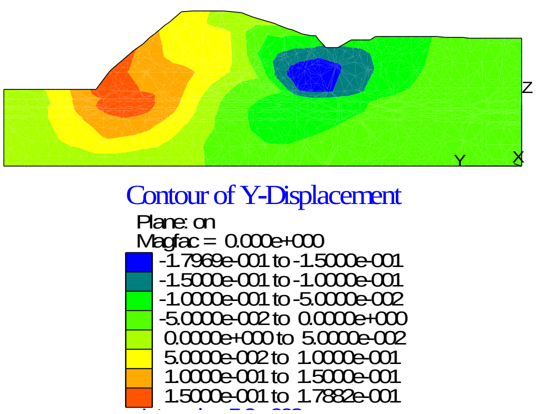


Figure 6: Horizontal displacement field under the current height.

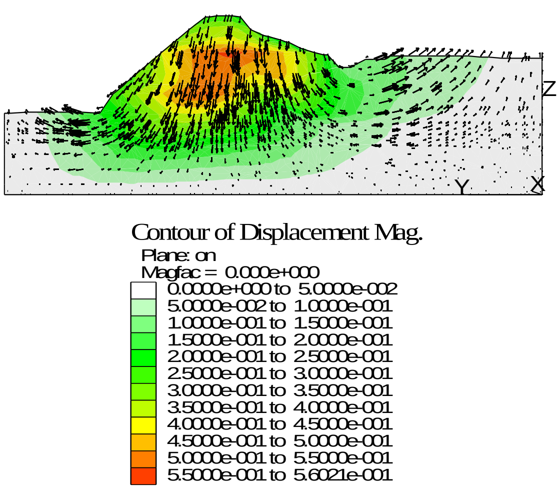


Figure 7: Displacement field and arrow under the future height.

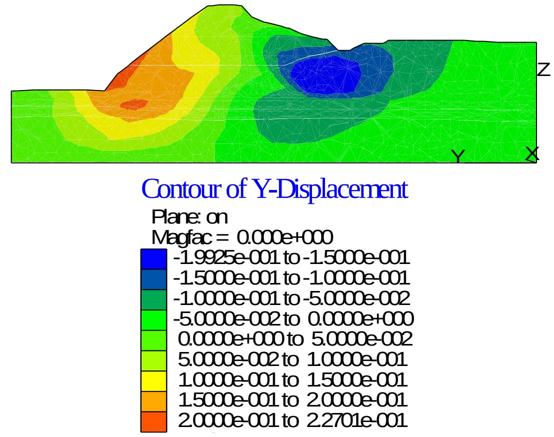


Figure 8: Horizontal displacement field under the future height.

The results suggest three potential failure modes of tailings dam under preloading: (1) Compressive shear zone in the outside ground is likely to induce sliding failure through the outer slope toe of tailings dam in cases where additional loadings are continued; (2) Local compression and shear failure could appear during the deformation process of tailings dam under gradual preloading; (3) Uplift failure might occur in tailings embankment as load increases with the increasing height of the mullock heap.

4.3 Safety risk analysis of tailings dam under gradual accumulation

According to Chinese technical codes, the safety factor of the tailings dam in this example project should not be less than 1.25 under normal operating conditions. The internal shear strength reduction method of FLAC^{3D} was adopted to calculate the safety factors of tailings dam with different heap heights and to determine the potential slip surface position. The safety factor of tailings dam was 1.28 under the present heap height of 38.5 m (Figure 9), which would reduce to 1.23 when the mullock heap height increased to 42.0 m (Figure 10). This would constitute a lack of safety reserve, and therefore the heap height should not be increased.

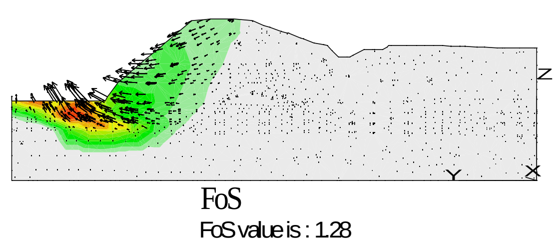
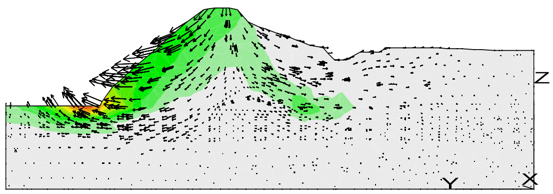


Figure 9: Potential slip surface and safety factor under the current height.



FoS
FoS value is : 1.23

Figure10: Potential slip surface and safety factor under future height.

5. CONCLUSION

It is concluded from liquid-solid coupling analysis that there are three potential failure modes of tailings dam under preloading. Under present conditions, the tailings dam meets safety requirements whereas in the event of additional heightened heap, safety requirements would not be met.

According to the above results, these engineering countermeasures were put forward: The height of the present heap must be cut to satisfy the stability requirement under the condition of rain infiltration. Sound monitoring and regular inspections should be established to ensure the safety of the tailings pond operation. The engineering practice showed that these safety measures achieved good results.

6. ACKNOWLEDGMENTS

This work was financially supported by the National Natural Science Foundation of China (51474188; 51074140; 51310105020) and the Natural Science Foundation of Hebei Province of China (E2014203012), 2015 Endeavor Research Fellowship and the Program for Taihang Scholars, all these are gratefully acknowledged.

7. REFERENCES

Bussière B., Chapuis R.P. and Aubertin M. (2003) Unsaturated flow modeling for exposed and covered tailings dams. In: The Montreal ICOLD Conference, Montreal, pp. 1-20.

Chakraborty D. and Choudhury D. (2009) Investigation of the behavior of tailings earthen dam under seismic conditions, American Journal of Engineering and Applied Sciences, Volume 2, pp. 559-564.

Chen D.Q., Wang L.G. and Li G. (2008) Analysis of tailing dam’s stability, Journal of Liaoning Technical University (Natural Science), Volume 27, pp. 349-361.

Hu M.J., Guo A.G. and Chen S.Y. (2004) Reflections on anti-slide stability analysis of a gangue dam, Rock and Soil Mechanics, Volume 25, pp. 769-773.

Li G.Z., Li P.L. and Xu H.D. (2005) Tailing dam stability analysis based on structural confidence level, Gold, Volume 26, pp. 48-50.

Li Q., Zhang L.T., Qi Q.L., Zhou Z.L. (2012) Instability characteristics and stability analysis of a tailings dam based on fluid-solid coupling theory, Rock and Soil Mechanics, Volume 33, pp. 243-250.

Lou J.D., Li Q.Y. and Chen B. (2005) Tailing-dam math simulation and stability analysis, Journal of Hunan University of Science & Technology (Natural Science Edition), Volume 20, pp. 58-61.

Shakesby R.A. and Richard W.J. (1991) Failure of a mine waste dump in Zimbabwe: Causes and consequences, Environmental Geology and Water Sciences, Volume 8, pp. 143-153.

Strachan C. (2001) Tailings dam performance from USCOD incident-survey data, Mining Engineering, Volume 53, pp. 49-53.

Valenzuela L. and Barrera S. (2003) Seismic design of Los Quillayes tailings dams in Chile, In: The 12th soil mechanics and geotechnical engineering Panamerican conference, Massachusetts, pp. 2235-2240.

Yin G.Z., Li Y., Wei Z.A., Jing X.F. and Zhang Q.G. (2010) Regularity of the saturation lines' change and stability analysis of tailings dam in the condition of flood, Journal of Chongqing University (Natural Science Edition), Volume 33, pp. 72-86.