Mechanical Stability of a Tailings Dam Incorporating Principles of Unsaturated Soil Mechanics

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Abstract. Tailings dams are an alternative for the final storage of waste produced by the metallurgical mining industry. Unlike water reservoir dams, tailings dams have the particularity of requiring a detailed analysis of the post-operation or closure phase. In this stage, the structure must be as safe as during the exploitation phase, even many years after the economic benefit has ceased. In the present, a significant number of historical cases of tailings dams accidents are known. In several cases, failures were generated by sliding of the dam slope after heavy rains. This article shows a simplified method for the evaluation of the mechanical stability of the embankment wall of a mining dam. The analysis accomplished considers the effect of humidity and suction changes on the shear strength of the materials. Through the implementation of a flow-stability coupled model, it is shown that in the probable occurrence of an extraordinary rainfall event, the studied dam maintains its stability with an acceptable factor of safety.

Keywords: Tailings Dams · Closure Stage · Coupled Model

1 Introduction

The mining industry oriented to the production of metallic minerals, generates large amounts of waste that need to be stored in a way that does not cause damage to the environment. In this context, tailings dams are an alternative for their final deposition.

Unlike water reservoir dams, tailings dams have the particularity of requiring a detailed analysis of the closure phase. In this stage, the structure must be as safe as during the exploitation phase, even many years after the economic benefit has ceased. Consequently, it is difficult to define the extension in time of the closure stage (500 years, 1000 years or in perpetuity), which implies difficulties for the statistical treatment of extraordinary design events (Oldecop and Rodríguez 2006).

According to the analysis of historical cases of tailings dams accidents that have occurred, the failure of the dam slope or the body of the dam together with its foundation are identified as the most frequent form of failure. In a significant number of failure cases, it is known that the accidents were preceded by a period of heavy rain (Oldecop and Rodríguez 2007).

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This article shows the application of a simplified method for the evaluation of the mechanical stability of the slope of a mining dam. For this case, the effect of humidity and suction changes on the shear strength of the dam component materials has been analyzed.

The geotechnical structure selected as a study case is part of a mining project located in Neuquén, Argentina. The tailings dam was operational from 2002 to 2015 and is currently in its closure stage.

The region where the dam is located is characterized by a humid cold climate. Precipitation can occur in the form of rain or snow. The amount of total precipitation oscillates between 500 and 700 mm/yr. The hydrometeorological predictions made for the sector indicate that the maximum probable precipitation (PMP) may be greater than 473 mm in 24 h.

The analyzes shown allow obtaining the stability of the tailings dam during a wetting process derived from extraordinary rainfall. This was achieved by implementing a flow-stability coupled model.

2 Method

The method applied is based on a calculation routine that consists of a flow-stability coupled analysis. This routine was applied using the Slide® software from Rocscience Inc. (EDU-2021/22-A-1, Licence 21036-001).

First, a unsaturated flow numerical model was developed by implementing the Groundwater Analysis module. In this stage, a steady-state and a transient seepage analyses were made. These two models allowed us to interpret the variation of the pore pressures derived from the application of the extreme rainfall on the dam.

Finally, the analysis of the mechanical stability of the dam slope was made by applying the Slope Stability module, including the pore pressures resulting from all stages of the flow model. In this stage, temporary Factors of Safety (FoS) were calculated by the Limit Equilibrium Method, according to the Simplified Bishop method.

3 Flow-Stability Model. Study Case

The mining dam studied is a storage structure of conventional tailings. The embankment wall was built with the coarse soil fraction of the tailings (sand); while the fine fraction (slimes) was stored in the deposit. The deposition sequence of both materials was performed adopting a construction system by the up-stream method. The cross section of the dam is shown in Fig. 1.

In Fig. 1 it can be seen that the cross section includes a reinforcement and protection rockfill on the outer slope of the dam. Inside the dam there are areas made up of transition materials that perform filter and drain functions. These two components were built with selected granular soils from deposits located in the vicinity of the project.

Figure 2 shows the granulometric composition curves of the materials that forms the tailings dam cross section.

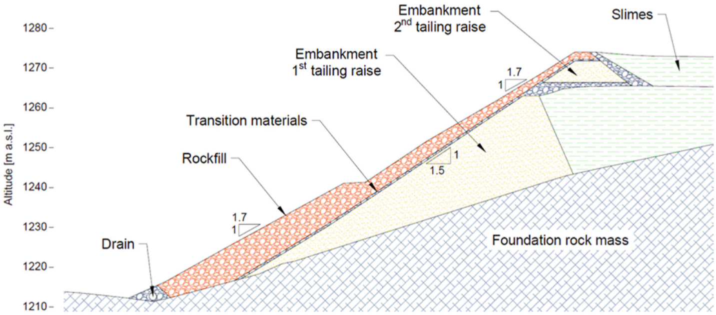

Fig. 1. Cross section of the tailings dam

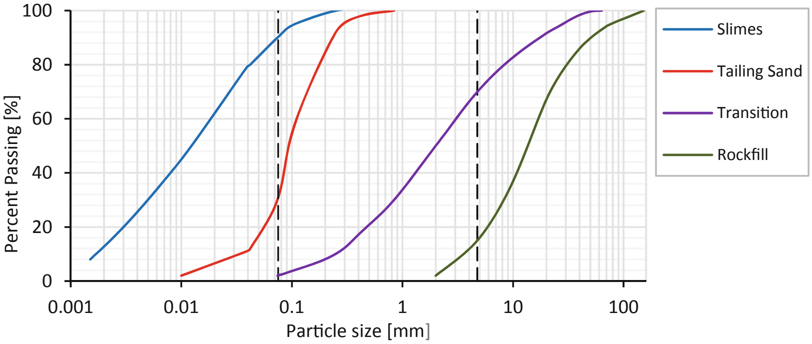

Fig. 2. Granulometric curves of the materials

3.1 Hydraulic Conductivity Functions

The elaborated flow model allows simulating the evolution over time of a moisture front in an unsaturated medium. The hydraulic behavior of the tailings dam materials has been defined from hydraulic conductivity functions. These functions are used to calculate pore pressure fields over time, which are exported to the mechanical stability model to estimate soil shear strength under unsaturated conditions.

The hydraulic conductivity functions were calculated from simplified estimation models. The sequence to develop these functions is summarized below:

1. Estimation of the Soil-Water Characteristic Curves (SWCC) of each material with the adjustment model of Fredlund and Xing (1994). The adjustment parameters of this model (a_f, n_f, m_f, ψ_{res}) were calculated using Fredlund et al. (2002) method. Figure 3 shows the SWCCs for each dam material.
2. Definition of saturated hydraulic conductivity coefficients (k_v^{sat}) based on available data on the dam. Table 1 shows the values used.
3. Estimation of the hydraulic conductivity functions of tailings dam material using Fredlund, Xing and Huang (1994) method. This model is presented in Eq. (1). Figure 4

Table 1. Saturated hydraulic conductivities of the dam materials

Material	k_v^{sat} [m/s]	k_h^{sat} [m/s]
Tailing sand	$4{,}7x10^{-6}$	$4{,}7x10^{-6}$
Slimes	$5{,}0x10^{-8}$	$5{,}0x10^{-7}$
Rockfill	$1{,}0x10^{-2}$	$1{,}0x10^{-2}$
Transition	$6{,}2x10^{-4}$	$6{,}2x10^{-4}$
Foundation rock mass	$1{,}0x10^{-12}$	$1{,}0x10^{-12}$

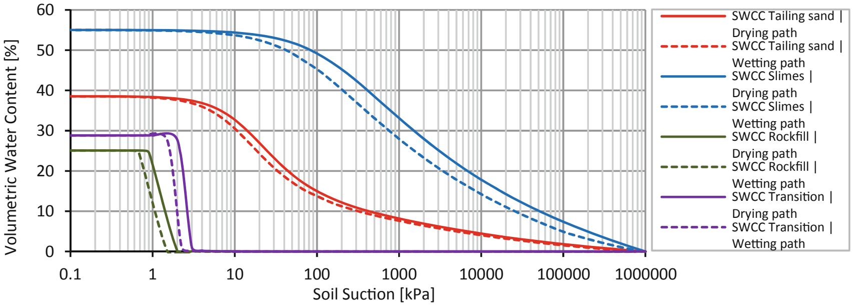

Fig. 3. Soil-Water Characteristic Curves (SWCC) of the dam materials

shows the calculated functions.

$$k_r(\psi) = \frac{\int_{Ln(\psi)}^{b} \frac{\theta(e^y)-\theta(\psi)}{e^y}\theta'(e^y)\cdot dy}{\int_{Ln(\psi_{AEV})}^{b} \frac{\theta(e^y)-\theta s}{e^y}\theta'(e^y)\cdot dy} \tag{1}$$

In Eq. (1), the integration limits are $b = Ln(10^6)$ and $Ln(\psi_{AEV})$ that represent the residual suction and air-entry values, respectively. $\theta'(e^y)$ is the derivative of the SWCC and y is a dummy variable of integration. θs is the saturated water content.

The models used to obtain the SWCCs and the hydraulic conductivity functions allow calculating the drying paths of both functions. To estimate the wetting paths, and show the hysteresis effect on the curves, a horizontal translation of the drying paths were applied following the recommendations of Fredlund et al. (2012).

3.2 Shear Strength Parameters

The model used simulates the unsaturated shear strength of the materials using the Mohr-Coulomb criterion extended to unsaturated soils (Fredlund et al. 1978), which is formulated as follows:

$$\tau_{unsat} = c' + (\sigma - u_a)\tan\varphi' + (u_a - u_w)\tan\varphi^b \tag{2}$$

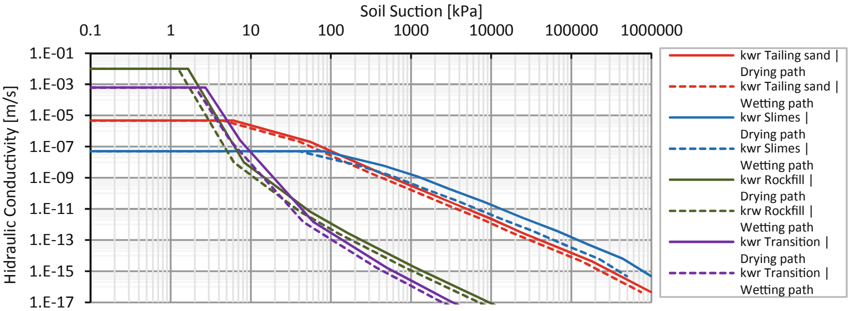

Fig. 4. Hydraulic conductivity functions of the dam materials

Table 2. Geotechnical properties and shear strength parameters of the dam materials

Material	SUCS	γ_d [kN/m^3]	c´ [kPa]	φ´ [°]	tan φ^b [°]
Tailing sand	SM	16	0,0	34	Θ_n tan φ'
Slimes	ML	12	0,0	17	
Rockfill	GW	21	0,0	40	
Transition	SP	19	0,0	37	

where τ_{unsat} is the shear strength of the unsaturated soil, c´ is the effective cohesion at zero suction (saturated soil), φ´ is the effective internal friction angle (saturated soil), φ^b is the angle that defines the rate of increase of τ_{unsat} with respect to the suction of the soil, $(\sigma\text{-}u_a)$ is the net normal stress on the failure plane and $(u_a\text{-}u_w)$ is the matric suction of the soil at the failure plane.

The shear strength properties in saturated condition (c´ and φ´) were obtained from available data.

For the estimation of φ^b, the model applies a non-linear expression using the normalized moisture content (Θ_n) obtained from the SWCC, so that: $[\tan \varphi^b] = [\Theta_n \tan \varphi']$ (Vanapalli et al. 1996). Table 2 shows the basic geotechnical properties and shear strength parameters (saturated and unsaturated) of the dam materials.

3.3 Hydraulic Boundary Conditions

The steady-state seepage model uses the total hydraulic heads (h_T) as boundary conditions. These hydraulic heights were applied to both lateral side of the calculation section. The values used have been obtained from the groundwater monitoring system in the body and surroundings of the dam.

In the transient seepage analyses, in addition to the hydraulic heads h_T, a time-varying infiltration rate ($q_{(t)}$) was implemented over the upper contour of the model. This boundary condition allowed simulating a rainfall infiltration process into the dam body.

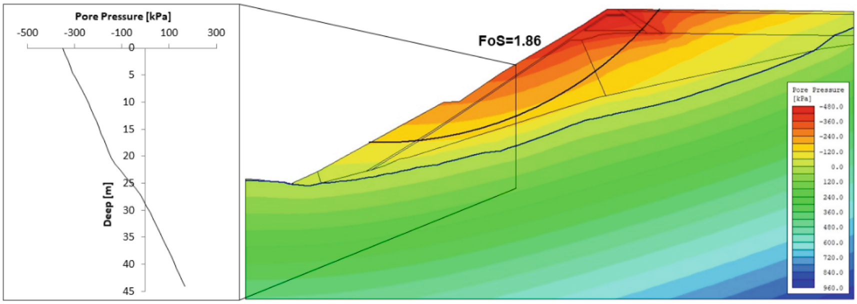

Fig. 5. Result of the flow-stability coupled model in steady-state

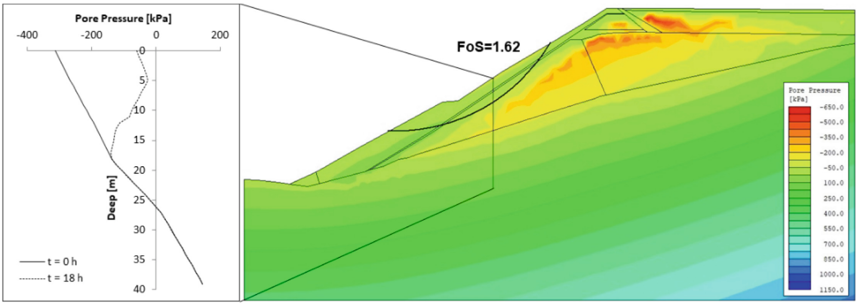

Fig. 6. Result of the flow-stability coupled model in transient analysis (Stage 6 | t = 18 h)

4 Results

Figure 5 shows the result obtained in the initial steady-state flow model (without precipitation). With it, the initial position of the water table and the pore pressures inside the dam were obtained. Under these conditions, the mechanical stability of the slope was computed, obtaining a Factor of Safety (FoS) of 1.86.

Then, the transient flow simulation was calculated, including the infiltration derived from the occurrence of an extraordinary rainfall (PMP) lasting 24 h. Based on this, a simulation period of 48 h was adopted and the FoS was simultaneously computed every 3 h of simulation. Figure 6 shows the result obtained for the calculation stage with the lowest FoS (1.62).

Figure 7 shows the evolution of the FoS during the entire simulation period (d = 48 h) and its temporal relation with the extreme rainfall event (d = 24 h).

5 Conclusions

The results of the flow-stability coupled model show that the initial Factor of Safety (FoS) of the dam slope in steady-state conditions is 1.86. Once the transitory simulation has started, the FoS decreases until it reaches a minimum of 1.62 at 18 h after the storm initiation or 8 h after the rainfall peak. The decrease in the factor of safety over time is a consequence of the moisture front advance towards the interior of the dam.

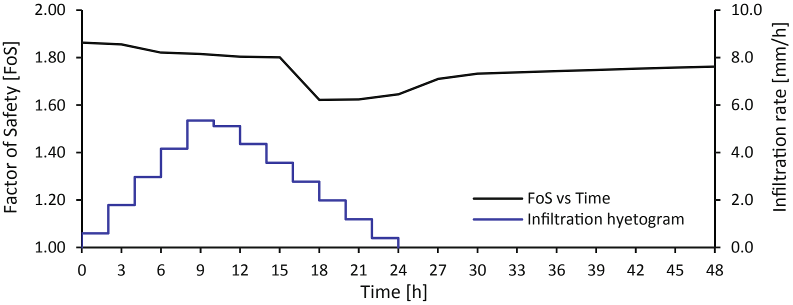

Fig. 7. Temporal variation of FoS

To define the acceptability of the FoS, the load conditions modeled in each simulation (steady-state and transient) must be considered and related to analogous scenarios proposed in technical reference guides such as ANCOLD (Australian National Committee on Large Dams, 2019), CDA (Canadian Dam Association, 2019) or USACE (U.S. Army Corps of Engineers, 2003).

For scenarios involving long-term loading conditions (steady-state seepage and effective shear strength parameters), the guidelines recommend a minimum FoS of 1.5 for the dam slope stability calculated by the limit equilibrium method.

For scenarios that include transient or accidental loads (earthquake, rapid drawdown, etc.), normally the minimum recommended factor of safety decrease to values of 1.1 to 1.3. The temporary increase in pore pressures inside the dam body derived from the occurrence of an extraordinary rainfall event can be considered as a scenario of accidental loads.

As indicated, the results calculated with the flow-stability coupled model in steady-state (FoS = 1.86) and transient (FoS = 1.62) conditions, show an acceptable level of stability according to the mentioned acceptability criteria.

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