# Analysis of the climatic effects on the stability of a tailings dam

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**Abstract.** In recent times, mining dams have become the focus of more detailed investigations due to the increase in the frequency of incidents and accidents. Brazil has recently experienced two disasters resulting in loss of life and significant environmental damage. Consequently, the stability analysis and ongoing monitoring of these structures have become the focus of detailed investigations. This study aims to analyze the impact of climatic effects on the stability of a mining dam. Geostudio software will be used for 2D numerical modeling to develop models for seepage and stability analyses. The models will incorporate climatic factors such as rainfall, evapotranspiration, relative humidity, and temperature to achieve the desired results. The findings will be presented in terms of the safety factor over time, focusing on how stability varies under the influence of climate.

**Keywords:** Dams, Mining, Climatic, Seepage, Stability.

## 1 Introduction

Mining dams are structures constructed to contain tailings, which are by-products of the mineral extraction process. They are designed to store solid waste mixed with water and chemicals resulting from mining activities. These dams are indispensable for mining operations, but their stability is a source of concern due to the potential risks that could lead to environmental and social disasters. As a result, they are increasingly becoming a focal point in civil engineering discussions, given their crucial role in the mining industry.

The mining sector holds great importance in Brazil as one of the key drivers of economic development in the country. This industry annually generates thousands of jobs, attracts both domestic and international investments, and wields significant influence over the national GDP, according to the IBRAM [1]. However, the sector's development is contentious, particularly concerning communities residing near mining operations. According to Duarte [2], many communities suffer from water and soil contamination, improper disposal of waste resulting in environmental hazards, and risks to the safety of downstream inhabitants due to mining activities, notably concerning dam safety.

The study of stability in mining dams is multidisciplinary, combining knowledge from geotechnics, hydrology, geology, meteorology, among others. As presented by Azam and Li [3], the climatic effects play an important role in this stability study of dams, as weather conditions can directly affect the behavior of the materials that compose the structure, regional hydrology, etc. Some of the most relevant climatic effects are precipitation, relative humidity, temperature variation, and evapotranspiration.

The main objective of this study is to assess and ensure the structural integrity of a dam in terms of the factor of safety (*FoS*) under varying climatic conditions.

# 2 Problem Setting

## 2.1 Study Site

The dam studied is situated near Belo Horizonte city, in the Quadrilátero Ferrífero area. The Quadrilátero Ferrífero is an area located in the southeast of the state of Minas Gerais, resembling a square of approximately 7,000 km². Minas Gerais, the second most populous state in Brazil, following São Paulo, is located in the Southeast region of Brazil, and it encompasses extensive urban and industrial areas, according to the Brazilian Geology Society [4]. Moreover, it is the leading state in mineral extraction across the country. As of March 2024, there were 936 mining dams registered in the Integrated Dam Safety Management System (SIGBM) [5], with 341 located in Minas Gerais.

According to Silva [6] the Quadrilátero Ferrífero region features a warm-temperate climate characterized by two distinct seasons: a dry winter and a rainy summer. The annual average temperature is around 20°C. Rainfall is concentrated during the warmer months, typically between October and March, with the heaviest precipitation occurring in December and January.

## 2.2 Meteorological data

The meteorological data utilized in this study were sourced from the website of the National Institute of Meteorology (INMET) [7]. The information provided includes daily data on evaporation, precipitation, temperature (maximum, minimum, and average), humidity, wind, among other factors, from January 1991 to January 2023. For this study, a 5-year period will be examined, from January 2018 to December 2022. The data were collected the Conventional Station 83587, located in downtown Belo Horizonte. These data will be input into the Geostudio software for modeling infiltration and flow, considering the effects of rainfall, evapotranspiration, humidity and temperature in the region.

In Fig. 1, precipitation, evapotranspiration, temperature, and humidity trends over the years are presented. The graphs show that there are periods of high precipitation between October and March, with peak rainfall consistently occurring in December and January. The pattern of relative humidity over time (*t*) corresponds to precipitation trends: humidity decreases during dry periods and increases during periods of high precipitation. The evapotranspiration graph exhibits consistent values with occasional peaks throughout the year. This phenomenon can be attributed to the region's minimal annual variation in average temperature.

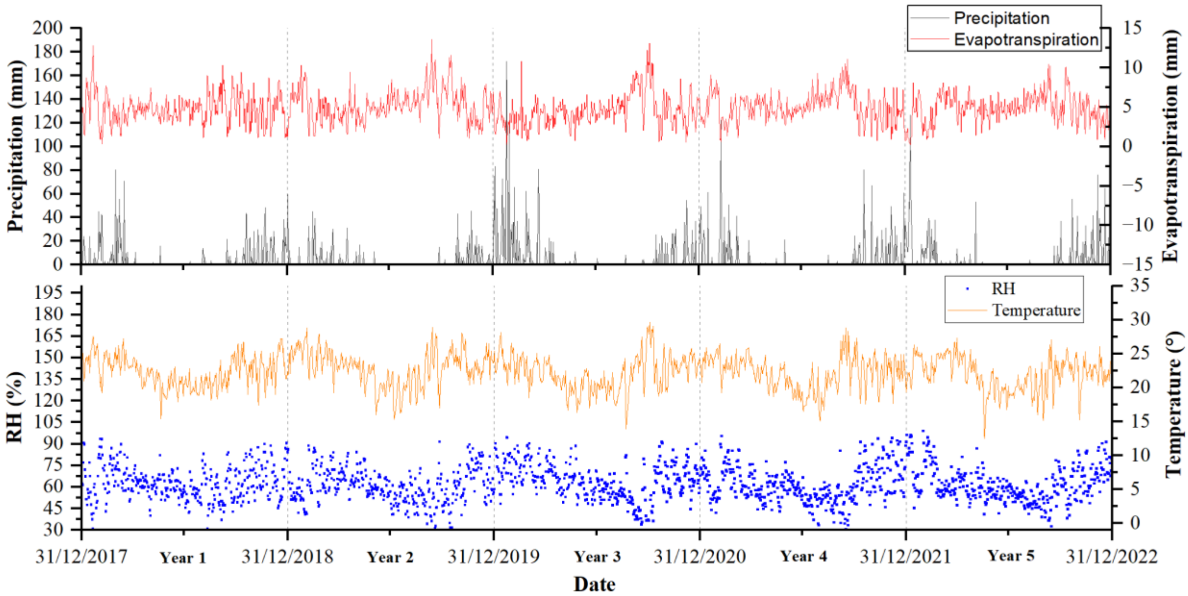


Figure 1. Meteorological Historical Data

### 2.3 Seepage data

SEEP/W, part of the Geostudio package, performs the 2D flow analysis of the model, considering various boundary conditions such as reservoir water level, meteorological conditions, downstream water level, etc.

In this study, flow analysis holds significant importance, particularly because it integrates climate analysis. Therefore, the hydraulic conductivity values of the materials were used from literature, assuming all materials were saturated except for the embankment material and filter, for which unsaturated parameters were used.

To characterize the water retention curve for the embankment and filter, several constitutive models can be adopted. In this case, the Van Genuchten model [8] was used, as presented in Siacara et al [9], defined by eq. (1) below, where $\theta$ is volumetric water content, $\theta_s$ is saturated water content, $\theta_r$ is residual water content, $h$ is suction, and parameters $n_v$, $m$, and $\alpha$ are empirical to fit the retention curve.

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha h)^{n_v}\right]^m}. \tag{1}$$

Also, through the parameters that characterize the water retention curve and the saturated hydraulic conductivity ($K$), the hydraulic conductivity function is defined to unsaturated materials by eq. (2).

$$K_w(\varphi) = K_{sat} \frac{\{1 - (a'\varphi)^{n-1}\left[1 + (a'\varphi)^n\right]^{-m}\}^2}{\left[1 + (a'\varphi)^n\right]^{\frac{m}{2}}}. \tag{2}$$

Table 1 presents the hydraulic conductivities data and parameters used in adjusting the retention curves and the hydraulic conductivity function. The Van Genuchten parameters were estimated as Gonçalves [10] suggested.

The governing equation used for modeling the water flow on the SEEP/W, is the following partial differential equation presented in eq. (3):

$$\left(\theta_w \beta_w + \beta\right) \frac{\partial u_w}{\partial_t} + m_w \frac{\partial\left(u_a - u_w\right)}{\partial_t} = \frac{\partial}{\partial_y}\left[\left(\frac{K_w}{\rho_w g}\right)\frac{\partial u_w}{\partial y} + K_w \frac{\partial_y}{\partial_y}\right]. \tag{3}$$

Where $K_w$ is the hydraulic conductivity, $u_w$ is the pore-water pressure (PWP), $\theta_w$ is the volumetric water content, β is the soil compressibility, $\beta_w$ is the water compressibility and $m_w$ are the slope on the water content function.

### 2.4 Geotechnical data

Soil types, in this study, were defined through Rezende's [11] data and information obtained from the ANM (National Mining Agency) website [5]. The Unit Weight ($\gamma$), and the Mohr-Coulomb parameters, such as Effective cohesion ($c'$) and the effective friction angle ($\varphi'$), are defined in Tab. 1.

The stability analysis will be conducted using the SLOPE/W software which is part of the Geostudio package. The PWP will variate at each step determined in the seepage analysis. In this study, every two hours, one step was registered, due to the boundary conditions (climatic factors). The factor of safety (*FoS*) will be estimated at each step, using the limit equilibrium method (LEM) with the Morgenstern-Price method. Geostudio [12] presents more detailed information about these methods.

Table 1. General parameters

| Material Name | Resistance Parameters | | | Hydrological parameters | | | | |
|---|---|---|---|---|---|---|---|---|
| | $\gamma$ (kN/m³) | $c'$ (kPa) | $\varphi'$ (°) | $K$ (m/s) | $\alpha$ (kPa$^{-1}$) | $n_v$ | $\theta_s$ | $\theta_r$ |
| Mining Waste | 23 | 0 | 35 | 1x10$^{-5}$ | - | - | - | - |
| Silty Clay Embankment | 23 | 17 | 30 | 1x10$^{-6}$ | 0.300 | 1.481 | 0.578 | 0.269 |
| Filter | 17 | 0 | 35 | 1x10$^{-3}$ | 0.38 | 2.391 | 0.426 | 0.034 |
| Foundation – Residual Soil | 18 | 15 | 30 | 2x10$^{-6}$ | - | - | - | - |
| Foundation – Saprolite | 19 | 60 | 30 | 1x10$^{-6}$ | - | - | - | - |

# 3 Methodology

## 3.1 Model definition

A tailings dam was examined. Its geometry consists of a 40 m height homogeneous embankment with a 1 m wide vertical filter connected to a drainage blanket composed of the same material. The foundation comprises a layer of approximately 15 meters of residual soil above the weathered rock layer (saprolite). The reservoir is filled with tailings, and the water level is 2 meters below the surface at an elevation of 80 meters. The section studied is presented in Fig. 2.

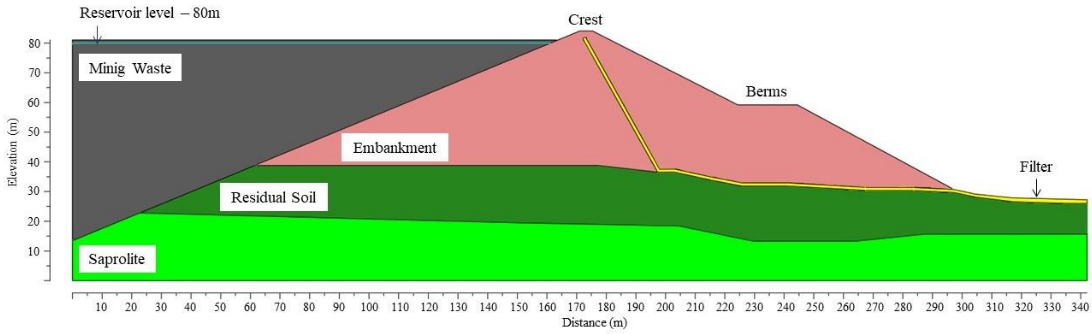


Figure 2. Dam geometry

## 3.2 Deterministic Analysis

The deterministic analysis considers constant values of hydraulic and soil resistance parameters within the studied structure. The study's steps are as follows:

(1) Definition of geometry, insertion of soil layers, and their parameters.

(2) Creation of an Initial Conditions scenario. In SEEP/W, this scenario involves a Steady State analysis with boundary conditions set as follows: the reservoir water level at 80 m, a downstream water level at 27 m, and a low-intensity rainfall at time $t = 0$ to define initial pore-water pressure (PWP). This initial condition, considering the low intensity rainfall, was used by Siacara et al. [13] and Rahimi et al [14], furthermore, it was suggested by Geostudio [15], justifying that this condition is more proper than applying a zero rainfall as a boundary condition, because this can ensure that the PWPs are stable representing the steady state condition.

(3) Creation of a transient analysis scenario. For the five-year analysis period, scenarios were created annually with the number of analysis steps defined accordingly. For scenarios analyzing dam behavior under rainfall alone and under full climatic effects, boundary conditions were set using step data point functions derived from the meteorological station discussed in section 2.2. Following these definitions, the transient analysis is performed using SEEP/W to establish the model's phreatic line and the PWP were calculated.

(4) Execution of a deterministic stability analysis. Using SLOPE/W, the initial PWP defined on steps 2 and 3, and the resistance parameters presented in the section 2.4, the *FoS* can be determined at every step of the analysis.

For this analysis, some tools may be defined. So, the slip surface shape was defined by the *"Entry and exit"* specification, which the user defines the area where the surface may start and finish. Also, the optimization option was chosen, allowing us to find the most critical failure surface in the analyzed problem. This brings us the benefit of identifying the lowest *FoS* value, thus promoting safety.

This step will be executed for three scenarios. The first one, without external meteorological effects, so it is a steady state analysis, as mentioned in step 2. And for the other two scenarios, the *FoS* will be calculated for the last year of the analysis, considering the transient analysis mentioned in step 3.

(5) Conclusion. The results and discussion for all three scenarios will be presented.

# 4 Results

Three scenarios were analyzed to investigate the climatic effects on the behavior and stability of a tailings dam. The results will be presented through an analysis of the PWP and the *FoS* over time. Additionally, the critical *FoS* will be presented, along with its corresponding critical time.

The three scenarios analyzed were:

(1) Analysis of flow and stability without external meteorological effects.

(2) Analysis of flow and stability considering only the external effect of precipitation.

(3) Analysis of flow and stability considering climatic effects such as evapotranspiration, precipitation, relative humidity, and average regional temperature.

## 4.1 Seepage analysis

The seepage analysis has a big role in the dam and *FoS* behavior. This analysis was conducted using the Finite Element Method (FEM), subdividing the model to reduce uncertainties and improve the analysis of localized effects, such as stress concentration. For the results, nine points (A to I) located in the embankment were studied to demonstrate the variation in PWPs over the last year of the analysis, see Fig. 3.

In Fig. 4 and Fig. 5, it is presented the PWP over time results for the scenarios 2 and 3, respectively.

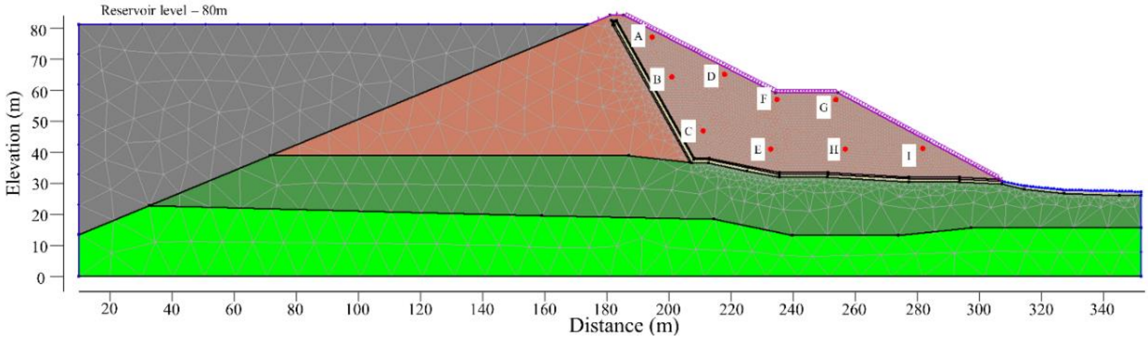


Figure 3. Analyzed points in the embankment of the dam

Through Fig. 4, it is possible to understand the variation of the PWPs over time. The points that are near the surface (A, D. F, G and I), present a more responsive variation due to the precipitation value. During the drought, the PWPs in these points tend to stabilize and reduce gradually. On the other hand, during the rainy season, these points present an important variation on the PWPs due to the rainfall infiltration.

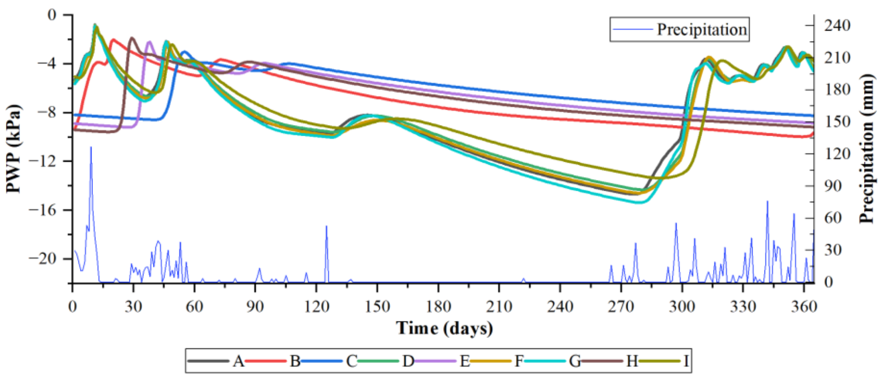


Figure 4. PWP in the embankment of the dam in scenario 2

Figure 5 presents the PWP over time for the scenario 3, that considers not only the precipitation effects, but also the evapotranspiration, temperature and relative humidity. As in scenario 2, the same points that are nearer to the surface, are more responsive to the climatic conditions. Also, these points reach a higher negative PWP (around -20 kPa), while in scenario 2, they don't reach over -16 kPa. That can be justified by the influence of suction due to the evapotranspiration inserted on the model.

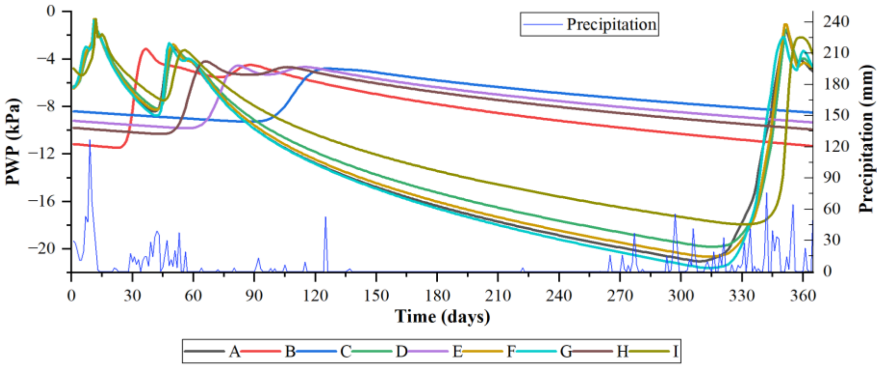


Figure 5. PWP in the embankment of the dam in scenario 3

## 4.2 Stability results

Figure 6 presents the comparison between the factors of safety of all three scenarios.

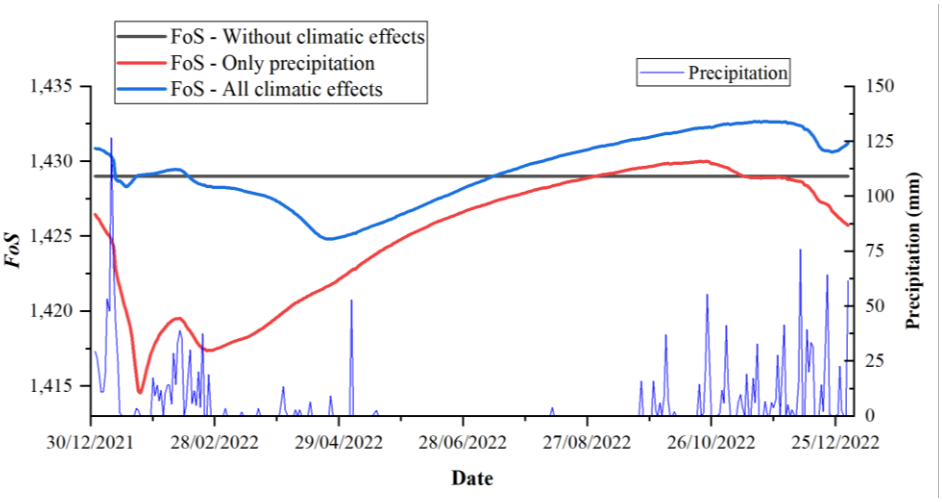


Figure 6. Comparison between the FoS for the three scenarios

The *FoS* for the scenario considering all climatic effects is higher and more constant than the one considering only precipitation. This can be justified by the presence of evapotranspiration throughout the analysis, so this effect will increase the suction in the surface area of the embankment, increasing the resistance, thereafter the *FoS*. When analyzing the *FoS* for scenario 3, a reduction is observed from the beginning of the year to the point of lowest *FoS* after a period of rainfall. However, shortly thereafter, during an extended period without precipitation, the *FoS* increases by 0.5%. This percentage is slightly higher in scenario 2, which considers only the effect of precipitation, and the *FoS* exhibits greater fluctuation after periods of more intense rainfall. Thus, after a long period without precipitation, the *FoS* increases by 1% from the lowest *FoS* recorded during the year under study.

Moreover, when examining the two *FoS* curves, it is evident that the *FoS* does not respond immediately to climatic effects. The safety factor is influenced by the intensity of recorded precipitation, but primarily by the cumulative amount of rainfall over time, considering the infiltration of water into the embankment. This effect can be observed from the beginning of the rainy season in October, as shown in Fig. 6.

The variation of the *FoS* can also be compared to the variation of PWP presented in Fig. 4 and Fig. 5, of the more superficial points. When the PWP decreases, the *FoS* increases, and the reverse is also true.

## 5 Conclusions

After this study, it is understood that the *FoS* of an tailings dam vary over time with the climatic effects. However, the variation is not of great magnitude since it varies in the second decimal place. This can be justified by the low variance of the PWP value in higher depth, due to the large size of the dam compared to the magnitude of the climate effects.

In addition to this, as pointed out in section 4.2, the *FoS* is directly affected by the variation of PWP. Therefore, given that the studied dam features an internal drainage system, which is crucial for controlling PWP within the dam's embankment, this study is significant to understand the importance of this drainage system. Because, in the event of a reduction in the efficiency of the internal drainage system, the PWP within the dam's embankment would increase, and consequently, the *FoS* would probably decrease.

In addition to the two limitations mentioned before, it is important to highlight the influence of changes in the reservoir level of the dam. This structure has a constant reservoir level, consequently not affecting the pore pressures acting within the embankment. Therefore, only climatic effects influence the behavior of these pressures. It is important to emphasize that in dams where the reservoir level undergoes significant variation, the pore pressures may behave differently from those presented in this report.

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