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Conceptual design of tailings dam and stability assessment

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Abstract
This work aims to present and discuss a conceptual project of mining tailings dam. Therefore, specific topics on tailings dams are visited and the characterization of materials constituting such structure is reviewed in the literature. Based on parameters available in the literature, a hypothetical dam was schematized and its stability was assessed via computational analysis (limit equilibrium and finite element flow analysis). Assessing eventual design changes (additional dam heightening) and hypothetical situations (collapses in the internal drainage), it is concluded that the schematic conceptual design presents itself viable and stable given the proposed geometry and the properties of materials considered. The importance of the internal drainage system for the dam´s stability was also identified.

Keywords: tailings dam; conceptual design; stability analysis.

Diseño conceptual de la presa de colas y evaluación de estabilidad

Resumen
Este trabajo tiene como objetivo presentar y discutir un proyecto conceptual de presa de relaves mineros. Por lo tanto, se abordan temas específicos sobre presas de relaves y se revisa la caracterización de los materiales que constituyen dicha estructura en la literatura. Con base en parámetros disponibles en la literatura, se esquematizó una presa hipotética y se evaluó su estabilidad mediante análisis computacionales (equilibrio límite y análisis de flujo de elementos finitos). Al evaluar posibles cambios en el diseño (aumento de altura de la presa) y situaciones hipotéticas (colapsos en el drenaje interno), se concluye que el diseño conceptual esquemático se presenta viable y estable dada la geometría propuesta y las propiedades de los materiales considerados. También se identificó la importancia del sistema de drenaje interno para la estabilidad de la presa.

Palabras clave: presa de relaves; diseño conceptual; análisis de estabilidad.

1 Introduction

Tailings dams are considered some of the largest man-made geotechnical structures. They have the purpose of disposing tailings from mining. Kossoff et al. [1] define tailings as the mixture of comminuted rock and fluids from the beneficiation process, presenting as a physical characteristic fine grain size and angular shape, and chemical composition dependent on the composition of the rock matrix and the reagents used in the process.

Typically, three basic construction methods are identified: upstream, downstream or centerline. These methods refer to the lifting technique and direction used. In the methods of raising the centerline and upstream, the upgrades are carried out partially over already disposed tailings. Although it generates significant savings with earth movement (less volume of material is used to the construction of the dam), it brings some complexity regarding the constructive control of the dam and the execution and control of drainage.

Azam and Li [2] present a worldwide history of failures in mining dams, where according to the authors' review, about 1.2% of mining dams presented some type of failure, against 0.01% of civil dams, in the last hundred years. In view of the aforementioned, the need for a full understanding of all the contours related to tailings dams and the correct conceptualization of the project to be developed is implicit. Curretly, several authors have attributed failures in tailings dams to construction and design problems, causing a generalized rupture [2–7].

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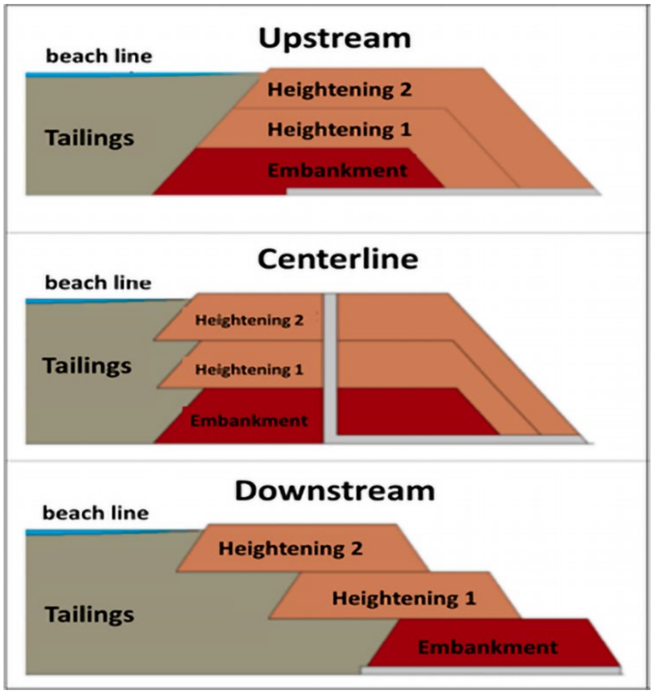

Figure 1. Tailings dam construction methods.
Source: Author

In this sense, considering the complexity of the theme and the latest incidents, the present work aims to evaluate the safety of a tailings dam executed by the upstream raising method.

1.1 Construction methods for tailings dams

There are three basic construction methods for tailings dams, although a combination of two or all three methods is common. These methods refer to the raising technique and direction used, whether upstream, downstream or along a centerline. These dams can be built with material from borrow areas or with the tailings from processing, provided they have been treated and meet the geotechnical specifications of the project. To this end, this tailings can be subjected to additional processes such as cycloning, for desliming, and is then called a hydraulic embankment [7]. De Araújo [8] comments that in the use of hydrocyclones, in his case study, the underflow (outlet with coarser material) has a percentage of 78% solids by weight and the overflow has 35%. As it is the portion with the lowest humidity and is typically more granular, the product from the underflow is destined for use as construction material for the elevations.

Fig. 1 shows the construction methods typically used in tailings dams.

As Fig. 1 shows, different from the downstream heightening method, in the centerline and upstream heightening methods, the heightening is carried out partially on tailings that have already been disposed of. Although this generates significant savings in earthmoving (there is a smaller volume of material used to build the dam), it brings a certain complexity in terms of constructive control of the dam and the execution and control of drainage.

2 Conceptual project

A conceptual study of a gold mine [9] was taken as a basis, where the systematic development from geological modeling, mine planning, processing and final configuration is presented. However, the disposal of tailings is not addressed. Thus, based on the study by Bicca et al. [9], there is a need to design technology for the disposal of generated tailings typically disposed in dams, in order to minimize the area impacted by this disposal. According to this study, due to the type of ore and beneficiation process (gold), practically all the tonnage of mined ore (which has gold content that makes it possible to process it) is processed and finally disposed of in the tailings dam. Considering an average gold content of 2.1 ppm (or grams of gold per ton of ore), it is clear that from each ton benefited only 2.1 grams on average will be product and will not be destined to the tailings dam. The rocks with no mineable content are destined directly into the sterile pile, without undergoing beneficiation.

Considering the mining planning, which aims at the best use of mineral resources and optimization of production processes, including the optimization of beneficiation, it is aimed a uniform production throughout the operation (life of the mine), and also the supply of ore at a relatively uniform rate to the beneficiation plant. Thus, except for anomalous situations (production failures, shutdowns, among others), there is a continuous annual generation of 1.45 million tons of tailings, with an average annual increase of 2.6 million tons, over the 13 years of operation.

The processes of beneficiation and concentration of gold ore are mainly comminution (crushing and grinding), physical-chemical (flotation), hydrometallurgy (leaching) and liquid-solid separation (thickening). The grinding process is more responsible for reducing the particle size and other processes by the addition of water, and finally the leaching and flotation processes (by the addition of reagents) are also responsible for changing the physicochemical properties of the generated waste.

2.1 Dam conceptualization

In the absence of data to adequately size the dam height, which should be sized according to the disposal rate and the elevation according to the topography of the site chosen for disposal, also in the absence of characterization of the materials to be used, for the conceptual design, parameters based on literature were adopted. In a conceptual way, in the absence of a specific dam location, which due to the topography would allow the dam height to be determined according to the occupied area. Table 1 presents an estimate of the occupied area and dam height, considering hypothetically a dam on flat terrain (which increases considerably the area occupied by the tailings).

Table 1.
Relationship between occupied area, average terrain slope and dam height.

Occupied Area (ha)	Dam Height (m)
60,57	30
45,43	40
36,34	50

Source: Author

As for geometry and properties of the dam, a range of case studies is available in the literature. Regarding to material characterization (beneficiation tailings) and geometries adopted, works of Silva et al. [8], Albuquerque Filho [10], Naeini and Akhtarpour [11], Rafael and Romanel [4], and Rout, Sahoo and Das [6] were consulted. Such works present characterizations of tailings from different ores (iron, copper and aluminum) and dam geometries. It should be noted that none of the studies listed above is explanatory as to the filter and/or drainage system used and its dimensions, however several textbooks [12,13] present options for drainage design configurations for earth dams (applicable to tailings dams) and filter sizing (referring to particle sizes).

It is also observed that the same materials (tailings), from mines of the same ore, have variability of geotechnical parameters, a fact that goes against the different beneficiation processes, which are responsible for giving the materials different geotechnical and hydraulic characteristics, such as demonstrates the work of Silva et al. [8]. This is due to the different processing routes, which comminute an ore in different particle sizes and use different reagents in the physical-chemical concentration processes.

To determine the hydraulic parameters of the materials that make up the structure (heightening and tailings), an option to laboratory tests or field tests, is the use of mathematical models for indirect determination of the parameters (kh, kv and/or kh/ratio) as presented by Shamsai et al. [14].

2.2 *Parameters and assumptions adopted*

Although most of the studies listed above deal with metal ore tailings, it was decided to use them as a basis for the development of the project, above all regarding the geometry and scale magnitude for the geotechnical properties of the design materials. It was decided to adopt, in a conservative way, geotechnical parameters with values close to the lowest values verified in the bibliography, since these referred to iron ore and copper tailings.

For the project, it was decided to consider dams made up of five materials (foundation, soft clay, landfill, disposed tailings and dense tailings) with properties according to Fig. 2, so that the parameters considered do not differ from the reality presented by real materials, although, for simplification, it was decided to consider isotropic materials.

As a construction method, due to its greater relevance (greater use for tailings dams) and economy (constructive, requiring less earth movement), as previously mentioned, the Upstream method of raising was chosen. Using elevations of 10 (ten) meters interspersed with benches of 10 (ten) meters, the slopes being considered with an inclination of 25°. As a preliminary project, a dam with 4 elevations was considered, totaling a global dam of 40 meters high. For the configuration of the tailings beach, the design parameters were used according to Silva [8] and Araújo [15], who based on empirical and observational models, considered in their studies the existence of two distinct phases, where the submerged portion presents greater inclination in relation to the emerged portion. This phenomenon is well described in works such as those by Araújo [15] and Machado [16], where they cite Vick apud Araújo [15].

Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kN/m2)	Phi	KS (m/s)	K2/K1	K1 Angle
landfill		19	Mohr-Coulomb	10	36	1e-007	1	0
filter/drain		20	Mohr-Coulomb	0	37	0.001	1	0
dense tailings		18	Mohr-Coulomb	0	32	3.47e-006	1	0
disposed tailings		18	Mohr-Coulomb	0	20	3e-005	1	0
foundation		20	Mohr-Coulomb	19	35	5e-006	1	0
soft clay		15	Mohr-Coulomb	18	0	5e-006	1	0

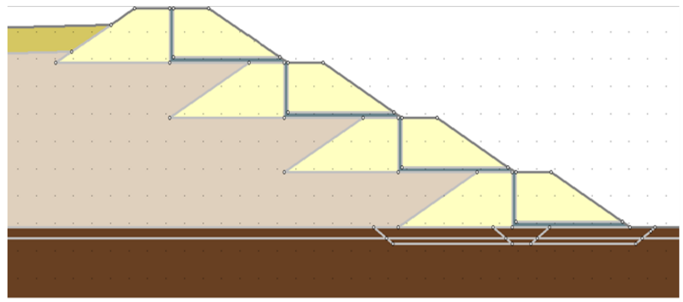

Figure 2. Dam layout and construction materials (software Slide).
Source: Author

As for the configuration of the tailings disposal, a tailing beach of 150 meters in length was considered between the theoretical pivot point of the tailings, at the dam, and the water line over which the tailings are submerged, typically with greater angulation as discussed by Silva [8]. As for the slopes adopted, a slope (i) of 0.5% was considered for the emerged tailings and 3.0% for the submerged tailings. Subsequently, the hypothesis of a water line under the tailings was observed, that is, a situation of greater risk and greater requirement for a filter/drainage system.

Regarding to the filter/drainage system, a chimney drain with a blanket was used in the project, in order to cover half of the foot and the entire central extension of the elevation, thus enabling its continuity during the elevations. The use of foot filters was also analyzed, as well as the option without a filter (hypothetical, system collapse). Fig. 1 shows the configuration of the proposed dam and a table with the constituent materials of the model.

3 Stability analysis

For the stability analysis of the dam project and design variations, limit equilibrium analyses were carried out using the software Slide 6. The piezometric line, hydraulic gradients and pore pressure distribution were determined in the same software, by numerical method, and later used in the analytical analysis, where they are influential in determining the Safety Factors (SF). For all analyzes, the Mohr-Coulomb rupture criterion was used. For the calculation of all safety factors, the Morgenstern-Price method was used, using a 50-slices discretization. This method was chosen because it is considered a rigorous method that adapts to different rupture surfaces and complex cases with different materials.

Regarding to the determination of parameters associated with the water flow, these were determined by considering a discretization by 4000 nodes and triangular elements, for all analyzes. These hydraulic parameters are determined by the software.

3.1 Project options

A dam project has several options and geometry solutions that can change the dam performance in different ways, typically the most evaluated aspect is the Safety Factor (SF), however other aspects such as the percolation of water by the massif (dam), pore pressure stresses and hydraulic gradients, must also be evaluated and may be of extreme interest when evaluating the piping and liquefaction phenomena.

To the project in question, it was decided to evaluate the variation of the water line or "tailings beach" position, and its influence on the stability of the dam; as well as the internal drainage system of the dam, by foot drain system and by its hypothetical failure. The hypothesis of an additional elevation and the existence of a low resistance layer on the foundation was also evaluated.

3.2 Analysis results

3.2.1 Ideal conditions

Ideal situations were considered as a reference model, without the need for foundation treatment, systems and an internal drainage connected to the foot and center of the slope, and mainly the "tailing beach" 150 meters away from the last slope. In such a situation we have an S.F. of 2.246. Fig. 3A shows the rupture surface and piezometric line, and Fig. 3B shows the pore pressure distribution.

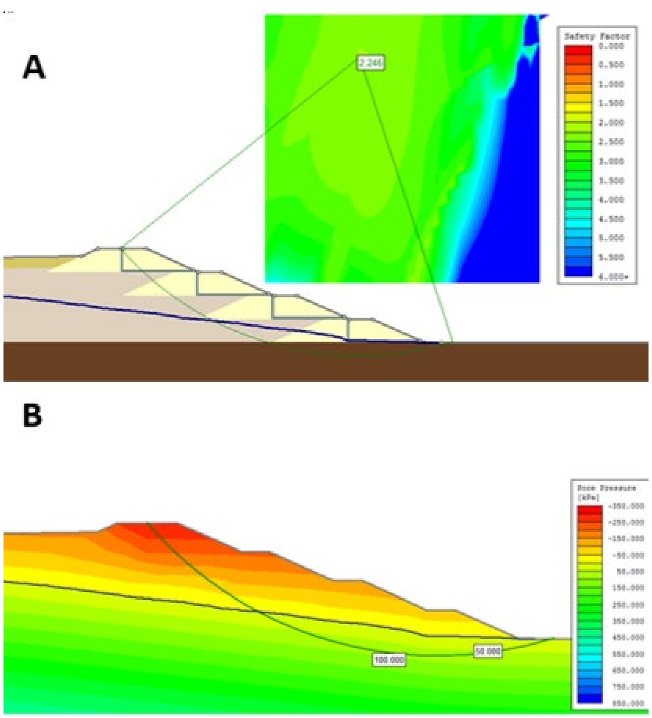

Figure 3. (A) Rupture surface in the dam in ideal situation and, (B) corresponding pore pressure distribution.
Source: Author

3.2.2 Scenario with water line under the tailings

For the analysis of the limit situation, the hypothesis of eliminating the tailings beach and raising the water level in the dam to 1.5 meters upper the tailings was evaluated (Fig. 3A). This hypothesis, as shown in Fig. 4, moves the piezometric line to the internal side of the dam. Fig. 4A shows the rupture surface, with 2.054 S.F., and Figs. 4B and 4C show the pore pressure distribution and hydraulic gradient at the base of the dam, respectively. This hypothesis is maintained in the following analyzes since it represents a risky scenario in comparison with the adequate distance from the "tailings beach" of the dam.

3.2.3 Scenario with water line under the tailings and hypothesis of drainage system collapse

In addition to the previous situation, a hypothetical collapse of internal drains was considered. This situation is considered to be the limit. In such a situation, an S.F. of 1.767 is estimated, as shown in Fig. 5A, however, such configuration represents concentration of hydraulic gradient and upward flow of water, as shown in Fig. 5C, situations that generate piping and liquefaction.

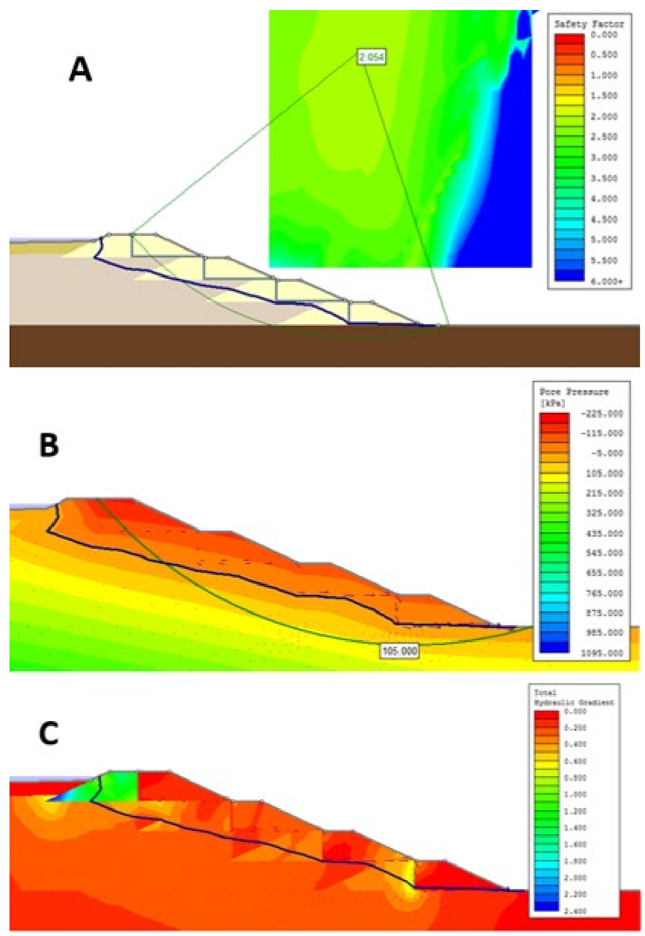

Figure 4 - (A) Rupture surface in the hypothesis of water level above 1.5 meters, (B) respective pore pressure distribution and (C) hydraulic gradient in the first dam.
Source: Author

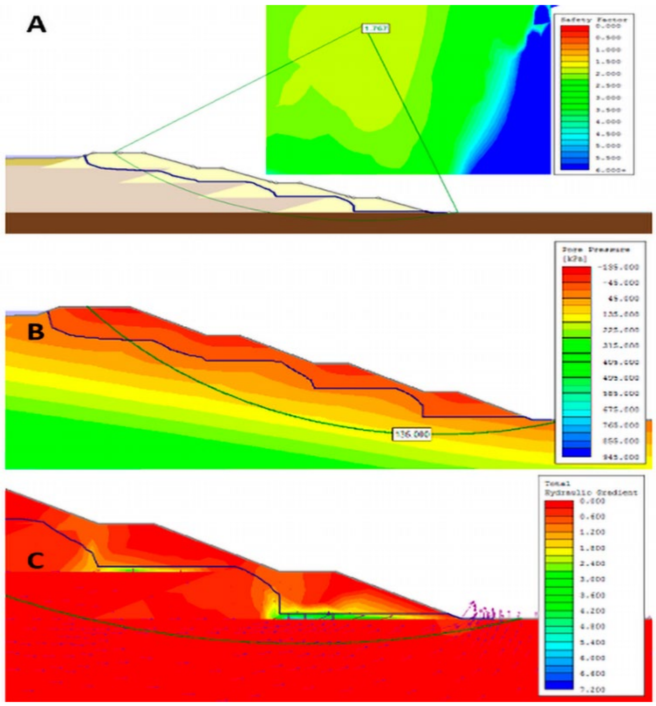

Figure 5 – (A) Rupture surface in hypothesis of collapse of internal drainage system and water level above the tailings, (B) respective pore pressure distribution and (C) accumulation of hydraulic gradient and internal water flow.
Source: Author

3.2.4 *Scenario with dam foundation under soft clay and subsequent foundation treatment (by partial layer replacement)*

In this scenario, the hypothetical occurrence of a soft clay layer (low strength) in the foundation of the dam, dike and tailings was considered. The hypothetical layer presents a thickness of 2 meters, considering it in the analysis we would have an S.F. of 1.332 and a rupture surface that would pass exactly through it (Fig. 6A). Considering a certain treatment of the foundation, by removing and replacing the layer under the initial dike, and advancing 1 meter under it, that is, crossing the layer. Fig. 6B shows the situation with the treatment of the foundation and its S.F. of 1.721.

3.2.5 *Blanket drainage system with water line under the tailings (1.5 meters above the tailings)*

This scenario was analyzed as an alternative configuration of drainage/filter system inside the dam, in order to evaluate both as a design option and as a hypothesis of eventual impairment of the vertical portion of the drainage/filter system. For that, in the model, only filter/drain of the "bar foot" type was considered. The hypothesis of a water level above the tailings was maintained. Fig. 7A shows the rupture surface and the piezometric surface line of the dam, where an S.F. of 1.994 was calculated. In Fig.s 7B and 7C, the pore pressure and hydraulic gradient distribution in the dam are represented.

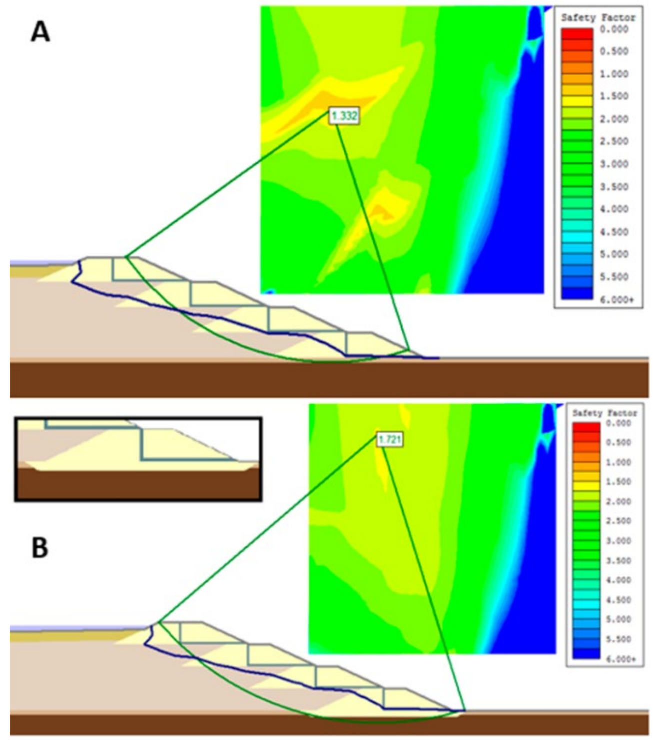

Figure 6. (A) Rupture surface and S.F. in the scenario of occurrence of "soft clay" layer under the dam and (B) Rupture surface and S.F. after treatment of the initial dike foundation.
Source: Author

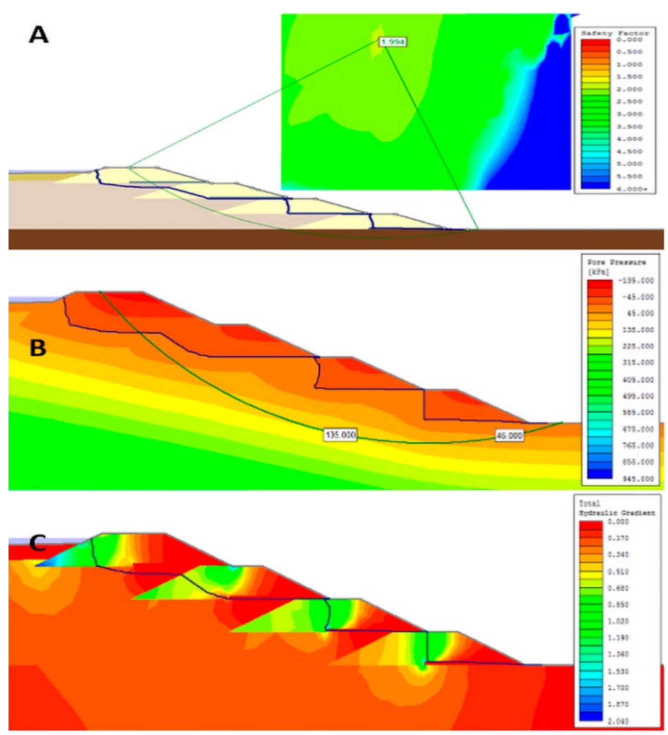

Figure 7. (A) Rupture surface in blanket drainage option and water level above the tailings, (B) respective pore pressure distribution and (C) hydraulic gradient accumulation.
Source: Author

3.2.6 Blanket drainage system only on initial dike and water line under the tailings (1.5 meters above the tailings)

In this scenario, the option for an internal drainage/filter only in the initial dam was analyzed. The hypothesis of a water level above the tailings was maintained. Fig. 8A shows the rupture surface and piezometric line of the dam, where an S.F. of 1.942 is calculated. In Figs. 8B and 8C, the pore pressure and hydraulic gradient distribution in the dam are represented.

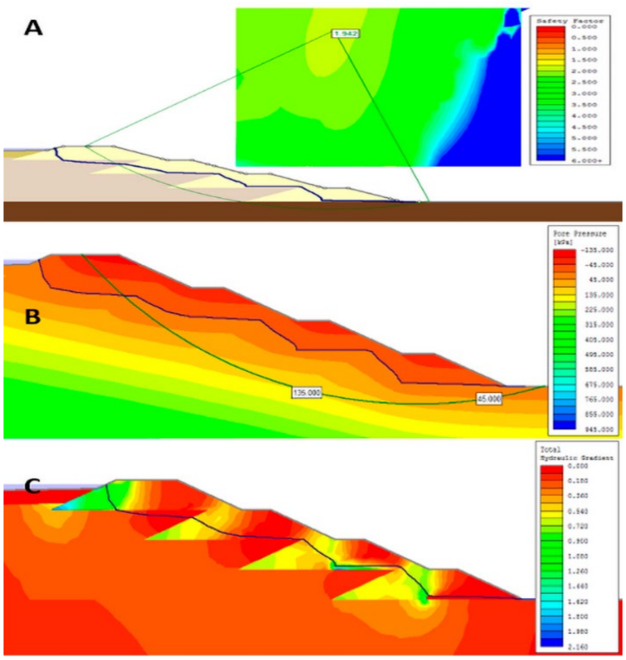

Figure 8. (A) Rupture surface in blanket drainage option only in initial dike and water level above the tailings, (B) respective pore pressure distribution and (C) hydraulic gradient accumulation.
Source: Author

3.2.7 Project Scenario considering additional heightening (5 heightening) and with a waterline under the tailings (1.5 meters above the tailings)

In this scenario, the hypothesis of an additional heightening of the dam and its impact on stability was analyzed. The hypothesis of a water level above the tailings was maintained. Fig. 9A shows the rupture surface and piezometric water line of the dam, where an S.F. of 1.899 is calculated. In Figs. 9B and 9C, the pore pressure and hydraulic gradient distribution in the dam are represented.

3.2.8 Project Scenario considering additional heightening (5 heightening) and with a water line at 150 meters from the dam

In this scenario, the hypothesis of an additional heightening of the dam and its impact on stability was analyzed. In this analysis, the “tailings beach” was located 150 meters from the dam.

Fig. 10A shows the rupture surface and piezometric line of the dam, where an S.F. of 2.105 is calculated. In Figs. 10B and 10C, the distribution of pore pressure and hydraulic gradient in the dam are represented. There is a reduction in pore pressure compared to the previous situation.

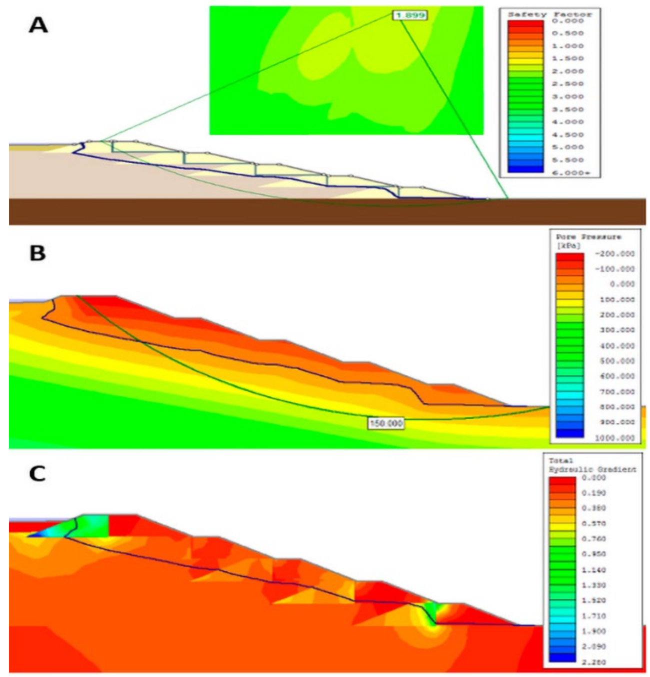

Figure 9. (A) Rupture surface in the event of additional heightening and water level above 1.5 meters, (B) respective pressure distribution and (C) hydraulic gradient.
Source: Author

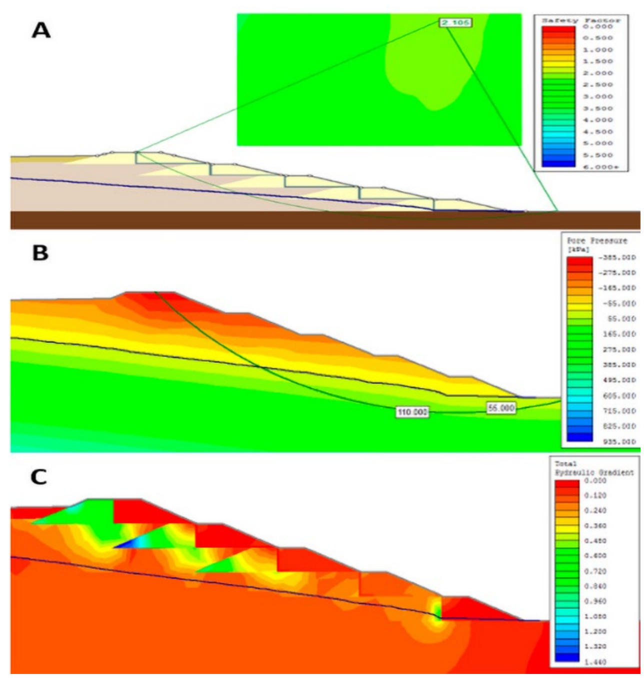

Figure 10. (A) Rupture surface in the hypothesis of additional heightening and water line at 150 meters from the dam, (B) respective pore pressure distribution and (C) hydraulic gradient.
Source: Author

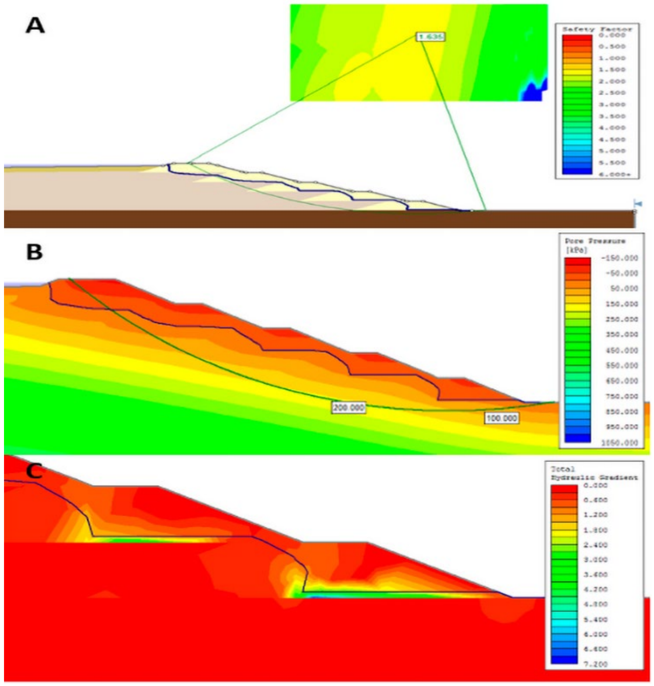

Figure 11. (A) Rupture surface under the assumption of internal drainage system and water level above the tailings, (B) respective pore pressure distribution and (C) accumulation of hydraulic gradient and internal water flow.
Source: Author

3.2.9 Project Scenario considering additional heightening (5 heightening), with water line at 150 meters from the dam and hypothesis of drainage/filter system collapse

In this analysis, besides the additional heightening and water level above the tailings, a hypothetical internal drainage collapse was considered. This situation is considered to be the limit.

In this situation, an S.F. of 1.635 is estimated, according to Fig. 11A; however, configuration represents hydraulic gradient concentration, as shown in Fig. 11C.

3.3 Analysis of results

The suggested tailings dam project met the safety requirements by the analytical method used, Limit Equilibrium. Under ideal operating conditions, water line at 150 m from the dam and internal drainage/filters in the proper configuration, the project presents a Safety Factor (S.F.) of 2.2; while under adverse conditions (collapse of internal drainage system and elevation of the water level), it still presents an S.F. of 1.8.

Although considering that the values obtained in the S.F.'s are above those recommended by standard (S.F. between 1.2 and 1.5), and thus the project is considered acceptable, other factors must be taken into account. First, since it is a hypothetical dam, several variables (topography, geology, materials, among others) are uncertainties. In this study, all parameters were estimated from the literature, while a real tailings dam project will certainly have laboratory test data to support the proposed solutions and access to greater resources for analysis.

Regarding to the analyzed scenarios, as expected, impacts on the S.F.'s, concentration of hydraulic gradients and pore pressures were verified; with variations in water level and position (tailing beach) and according to the internal drainage configuration. A scenario with an additional heightening (for a total of five heightening) was analyzed, raising the dam to a final relative height of 50 m. In this case, there is an S.F. of 2.1 in an ideal situation and an S.F. of 1.6 under adverse conditions, still within the safety limits.

Regarding to hydraulic gradients and pore pressures, it appears that these were sensitive to the changes tested. The lower dams and the internal filters are the most critical positions. As for pore pressure, it can be seen that in the proposed scenarios there was a variation along the critical rupture surface. These scenarios could (in the case of critical hydraulic gradients) cause triggers that lead to a dam rupture.

Based on the above analyses, it appears that the best measure to be taken to ensure the safety of the project is to move the water line away from the dam, which not only increases the dam's safety factors, but also reduces the pore pressures and hydraulic gradients. As for the internal filter/drainage systems, three options were evaluated: chimney drain with blanket, horizontal blanket drain and blanket drain only in the initial dike. According to the analysis carried out, a chimney drain with a blanket not only guarantees the highest safety factor, but also results in the smallest pore pressures within the dam slope and, is therefore, the most recommended option. The last analysis to be made would refer to safety due to liquefaction and piping; however, considering the design using a chimney drain with a blanket system in all heightening, and the respective hydraulic gradients (lower than the other options), which reduces the risk of landfill liquefaction; the dam can be considered stable at the level of the conceptual design.

4 Conclusion

The work showed the design of a tailings dam at the end of the mine operation, considering four heightening in ideal operating conditions (150 m away from the tailings beach and proper operation of the filters). In this condition, the dam has a S.F. of 2.25. Throughout the work, the effect of different variants that can occur during the operation of the dam was shown, including: (a) the increase of the water level almost to the crest of the dam, (b) problems with malfunctioning filters, (c) occurrence of soft clay in the foundation not detected in the design phase, (d) execution of a heightening level more than initially projected. All the analyzed conditions are responsible for the reduction of S.F. and may even reach values lower than those established by the standards. In this sense, it should be noted that such constraints must be taken into account in the project, as well as it is essential to ensure the proper functioning of all devices of a tailings dam (for example: filters), combined with an adequate periodic inspection (for example: measurement of piezometric levels).

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