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Review Article

Stability of slopes at the agua Dulce tailings dam in Potosí, Bolivia

Abstract

The Agua Dulce tail dam located in Potosi, Bolivia, belonging to the Santa Lucia Mining Company Ltda., it stores conventional tailings and has been constructed by the Aguas Arriba method. During its operation stage, the geometrical characteristics proposed in its original project were not met; Therefore, for the stability analysis of slopes, different models are proposed according to four parameters: section geometry, drainage condition, load condition and analysis method, through the GeoStudio 2012 program. The obtained results allow to define relations and influence between the variations of the parameters analyzed; agreeing that the closure of the tail dam is feasible under a ratio of the last slope of 1:2.34 to the closing level, guaranteeing the correct functioning of the bottom drains.

Keywords: slope stability, safety factor, mining, tail dam, tailings

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Introduction

Bolivia, mining country, is ranked 23 world ranking regarding the ICM (Index Contribution Minera) based on the non-fuel mining, which takes into account the dynamism of mining activity, the contribution to GDP and its contribution to mining exports.[1] Waste generated by this activity are deposited in tailings dams, the same as throughout the project stage must fulfill their chemical and physical stability, particularly the stability of the slopes. One of the major mining companies in Bolivia is the company Minera Santa Lucia Ltda., In charge of the tailings dam Agua Dulce. This dam is in pre-closure which is necessary to ensure that the final closure there of remain stable and safe regarding static analysis of their slopes;

Tails or tailings are the last residues of mineral processing where acquire a certain chemical aggressiveness product using chemical agents (lead arsenic, mercury, etc.). They have a muddy consistency sedimented mineral containing small fractions of rocks inert and safe in large volumes. Varying the solids content results in the existence of different types of tailings; in order to improve their physical behavior according to the highest solids content. Tailings types are conventional, thickened, paste and filtering, solids contents from 30%-55%, 40%-70%, 65-85% and above 85% respectively.[2]

Geotechnical characteristics are evaluated in the tailings are identical to those of natural soils. The main differences are a function of the preceding ore the tailing, tailing type, deposition time and distance. These characteristics determine its strength, permeability and compressibility, which in turn influences the stability analysis, filtration and deformation of tailings dam. Coarse particles of the tailings settle faster, especially near the discharge points while fine take longer to settle. The specific weights that can be found within the same dam to vary by 25%, which variation is inversely proportional to the solids content in the tailings.[3] Tailings have a high internal friction angle, product of the milling process suffering in mineral processing, besides eliminating weak particles by washing and transport. The higher degree of saturation to 85%, which generally means lower geotechnical stability and greater likelihood of rupture of the dam slope landslides and liquefaction.[4] This is due to several simultaneous occurrence hydraulic phenomena as capillary rise of the groundwater, the water supply involving pouring fresh tailings and infiltration of water runoff. which generally it implies lower geotechnical stability and greater likelihood of rupture of the dam slope landslides and liquefaction.[4] This is due to several simultaneous occurrence hydraulic phenomena as capillary rise of the groundwater, the water supply involving pouring fresh tailings and infiltration of water runoff. which generally it implies lower geotechnical stability and greater likelihood of rupture of the dam slope landslides and liquefaction.[4] This is due to several simultaneous occurrence hydraulic phenomena as capillary rise of the groundwater, the water supply involving pouring fresh tailings and infiltration of water runoff.

Tailings dams are geotechnical structures to store tailings stably and harmless to the natural environment, both physically and chemically, generating the least possible effect on the surrounding ecosystem. Tailings dam stored both solid and liquid, the same queues are used as building material of the embankment dam in a staged process, depending on the development of mining operations, in order not anticipate investment, reducing initial investment and anticipate changes in the processes of extraction and processing of minerals. The type of tailings dams is based on the stored tailings and disposal site; the most common are the dams on the surface, built under the methods Upstream, Downstream and Central Axle.

Colas dam "freshwater"

The tailings dam Agua Dulce (Figure 1) is located in the community of Agua Dulce, Tomás Frías Province, Department of Potosi, Bolivia. Tailings stored come from the treatment plant of the same name, which deals minerals zinc (Zn), lead (Pb) and silver (Ag), mainly from the Cerro Rico de Potosi and Melena Mina.

The dam is located at a site 60,000m^2, which stores 5000000m^3 of conventional tailings built by Upstream method; reaching 15meters high from the crown of the dam to a height boot closing. According to Law No. 1777,[5] of the Mining Code of Bolivia, this dam is classified as a dam high volume because accumulations of waste exceed 50,000m^3.

Response to this, to ensure the stability and safety of embankments dams large volume of tailings is considered a minimum FS 1.5.[6]

Figure 1 Tailings freshwater.

In these geotechnical works the presence of three main materials are distinguished: the floor of the foundation, the fill material that makes up the dam boot and stored tailings, whose properties are shown in Table 1. In addition, it is common the presence of a water mirror surface.

Raised models

The feasibility of closing the dam was analyzed under conditions constructive potential. Therefore, four amendments were created regarding the geometric section of the dam project, three changes in drainage conditions and three load conditions; creating 2 different models analyzed under methods Fellenius, Bishop and Morgenstern & Price.

Model 1 (Figure 2a) takes into account the drainage conditions and Model 2 (Figure 2b) is analyzed under the proposed conditions of loading, the description of the code patterns can be seen in Table 2.

Table 1 Geotechnical properties of materials tailings dam Agua Dulce

Material	ϕ^o	c (kPa)	Dry γ (kN/m^3)	saturated γ (kN/m^3)	k (m/s)
Floor foundation	25	7	17.6	19.4	1e-15
Dique boot	26	8	20	21.5	1e-8
Relave	31.53	10	19.5	21.2	2.82 e-7

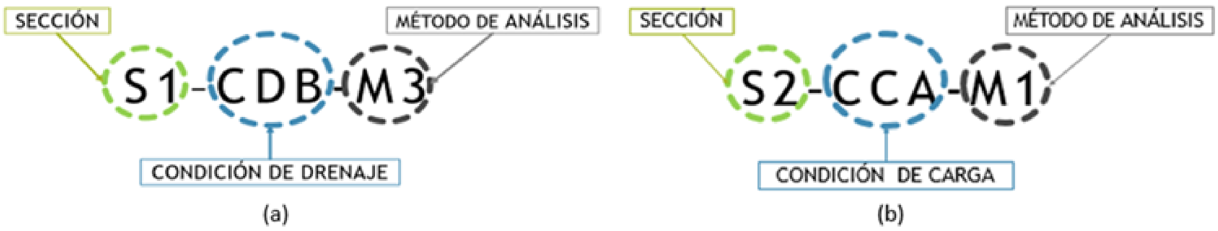

Figure 2 Identification code (a) Model 1; (b) Model 2.

Table 2 Parameters identification code Model 1 and Model 2

Parameters code	Code symbology	Description
Section	S1	Current section.
	S2	Section project.
	S3	Current section relave current draft.
	S4	Current project section that stores two types of tailings.
Drain condition	CDA	Condition mirrors water and drainage 6m foot of the slope of the dam upstream boot.
	CDB	Condition mirrors and drain water by the side of the road downstream of the dam boot.
	CDC	Condition mirrors water and drainage in the crown of the dam boot.
Load condition	CCA	Condition mirrorless water and concavity of the water body.
	CCB	Mirrorless condition water without concavity of the water body.
	CCC	Projection parking on the tailings dam Agua Dulce closed.
Analysis method	M1	Method Fellenius ordinary u.
	M2	Bishop method.
	M3	Morgenstern & Price method.

Citation: Huarahuara YRT, Harambouure YG. Stability of slopes at the agua Dulce tailings dam in Potosí, Bolivia. *Int J Hydro.* 2020;4(2):47–53. DOI: 10.15406/ijh.2020.04.00225

Sections patterned

The tailings dam Freshwater comprises a dam starting slope 1:2.2 upstream and downstream with an average height of 3,75m, whose crown 4.6m wide is placed at an altitude 3748m the increase in height by Upstream method was made with the construction of three berms located every five meters in elevation, slope downstream 1:3. The projection of the slope downstream of the third berm has been affected by changes in the construction stage; The original project proposes that this slope is 1:3, but is outlined with a 1:2.34, which casts doubt on the security guaranteed by the initial project. Therefore, changes in sections are made in the last slope, from level to level 3757.9m crown (3763m).

Section 1 (3a) has the current geometry of the dam, the last slope has a 1:2.34 and reaches the level 3761.7. Section 2 (Figure 3b) reaches the closing height with a slope 1:3. Section 3 (Figure 3c) reaches the closing height with a slope 1:2.34. Section 4 (Figure 3d) has the same geometry as Section 3, with the difference in dimensions from 3761.7 to 3763 (closing height) provides possible storage of a tailing with unfavorable geotechnical characteristics relative to the currently deposited, the geotechnical characteristics of this Relave 2 can be seen in Table 3.

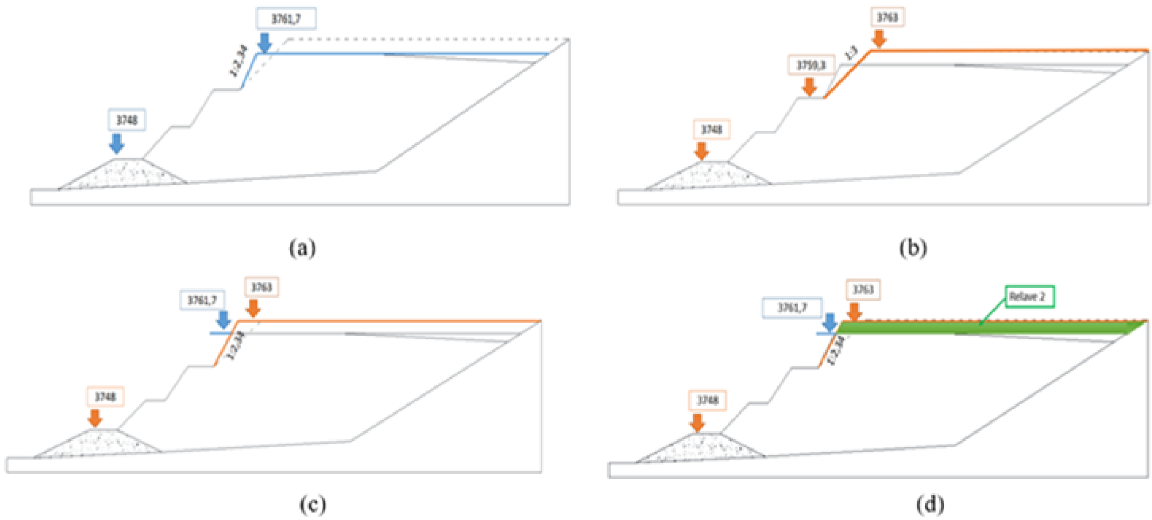

Figure 3 Sections modeled: (a) Section 1; (b) Section 2; (c) Section 3; (d) Section 4.

Table 3 Geotechnical characteristics of the Relave 2

Material	ϕ^{o}	c (kPa)	Dry γ (kN/m^3)	γ saturated (kN/m^3)	k(m/s)
Relave 2	25.22	8	21,45	23.32	2.82 E-6

Drainage conditions

The tailings dam Agua Dulce has drains bottom six meters above the foot of the slope upstream of the dam boot, geomembranes at the bottom of the dam to the crown of the dam boot and due to the presence of a water mirror surface there condition infiltration. Analysis slope stability in Model 1 was performed using an analysis filter and flow precedent established with Module PDES/W GeoStudio 2012 software with which the position of the upper current line in each section is determined.

Condition CDA (Figure 4a) considers the proper functioning of the drain line located six meters from the foot of the slope of the dam upstream boot. Condition CBD (Figure 4b) proposed that the free flow duct is in the roadside ditch Potosi- Uyuni located 50meters downstream of the dam boot. Condition CDC (Figure 4c) considers the drainage crown dam boot, providing the correct operation of geomembranes and clogged drains background.

Load conditions

Load conditions do not consider the existence of a water surface due to different factors such as evaporation or pumping water and corresponding reuse in the treatment plant, in order to reduce environmental impact, or as a precaution to the grant greater physical stability to the dam. Condition CCA (Figure 5a), the existence of the concavity caused by the prior existence of the sheet of water on the surface. Condition CCB (Figure 5b) assumes that the sealing surface is horizontal, product activity filling the concavity of the CEC Condition.

Condition CCC (Figure 5c) proposes the construction of a parking lot on the level of closure of the tailings dam and rehabilitation plan for the area affected by the tailings dam Agua Dulce area, taking into account a charge for light traffic 8.6kPa.

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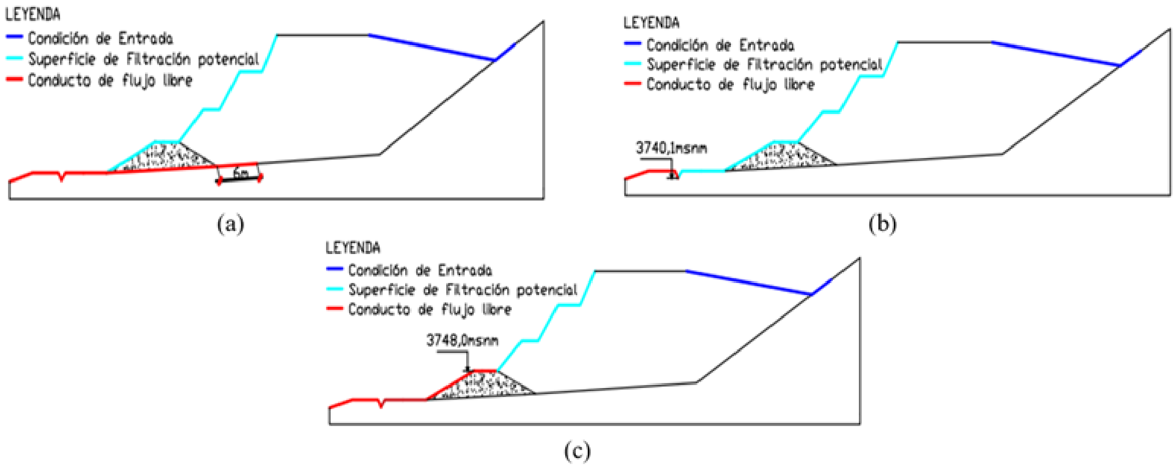

Figure 4 Conditions drain: (a) Condition CDA; (b) Condition CBD; (c) Condition CDC.

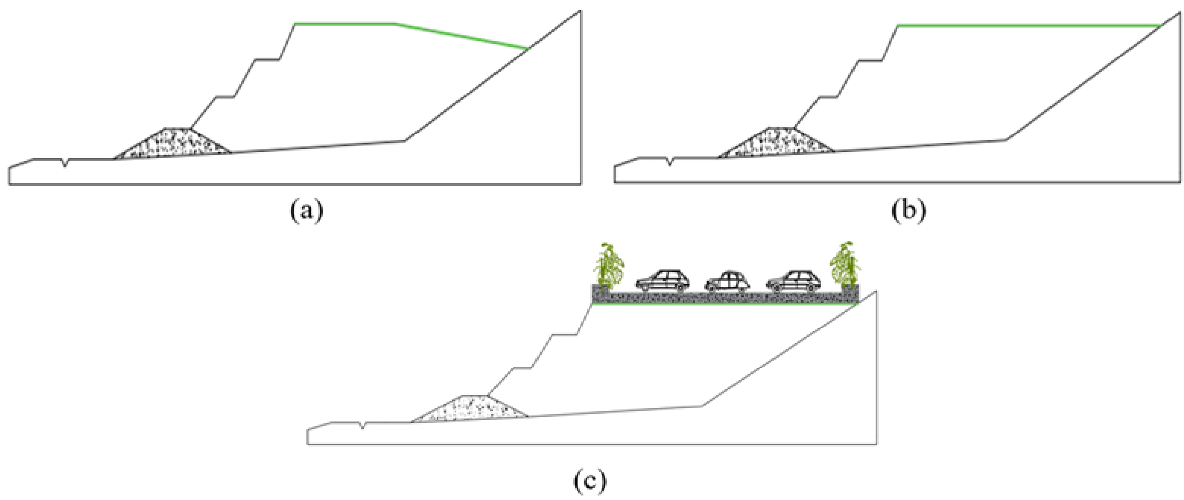

Figure 5 Charging conditions: (a) Condition CCA; (b) Condition CCB; (c) Condition CCC.

Results analysis of prey queue freshwater

Influence of variation of drainage conditions

With seepage analysis performed in Model 1 for drainage conditions the four sections were analyzed, these results are expressed in Table 4&Figure 6, by Bishop method. The results of Model 1 are greater than a FS 1.3 ensuring the stability of the tailings dam under all conditions drain raised; However, dam safety is only guaranteed in Condition CDA appreciate where FS greater than 1.5.

Influence of varying load conditions

Concerning the modeled sections not considered a surface infiltration (Model 2 with results shown in Table 5&Figure 7), the results in all cases are higher than the required 1.5FS Bolivian regulations, with which the stability and security of the tailings dam Freshwater under load conditions raised, appreciating also ensures that the results of Model 2 are similar quantitatively to each other; and variations between each load condition are minimal.

Influence of variation of the geometry of the sections

Varying the geometry of the sections is analyzed in both models (Table 6). Figure 8 compares Section 2 and 3, which correspond to the original project and built section, respectively; appreciating that variation in the slope regarding proposed in the original draft of the final slope downstream provides FS similar, resulting insignificant variation of the last batter for Guaranteeing slope stability of the tailings dam Agua Dulce.

Table 7&Figure 9 compare Sections 3 and 4 with the same geometry but different tailings stored between measurements 3761.7m and 3763m From said figure that seen under the same geometry variation is not significant FS qualitatively appreciating in drainage conditions the variation between the two sections is wider than under load conditions, appreciating that Section 4 is very unfavorable in Model 1.

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Table 4 FS obtained in Model I

FS drainage conditions						
Section	CDA		CDB		CDC	
	Model	FS	Model	FS	Model	FS
S1	S1-CDA-M2	1,828	S1-CDB-M2	1,453	S1-CDC-M2	1,356
S2	S2-CDA-M2	1,816	S2-CDB-M2	1,444	S2-CDC-M2	1,352
S3	S3-CDA-M2	1,793	S3-CDB-M2	1,444	S3-CDC-M2	1,348
S4	S4-CDA-M2	1,649	S4-CDB-M2	1,385	S4-CDC-M2	1,342

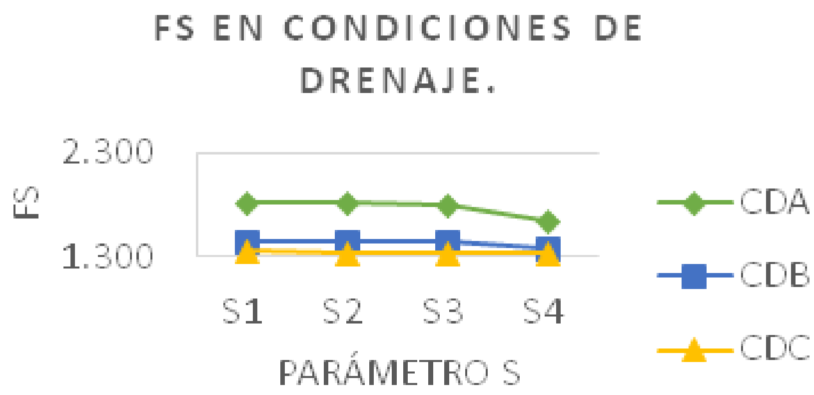

Figure 6 FS sections Model 1.

Table 5 FS obtained in Model I

FS load conditions						
Section	CCA		CCB		CCC	
	Model	FS	Model	FS	Model	FS
S1	S1-CCA-M2	2,088	S1-CCB-M2	2,083	S1-CCC-M2	-
S2	S2-CCA-M2	2,086	S2-CCB-M2	2,081	S2-CCC-M2	2,075
S3	S3-CCA-M2	2,086	S3-CCB-M2	2,080	S3-CCC-M2	2,075
S4	S4-CCA-M2	2,083	S4-CCB-M2	2,080	S4-CCC-M2	2,076

Table 6 Sections 2 and 3

FS sections of different slopes of the last slope of the dam.					
Condition		S2 (slope 1:2.34)		S3 (slope 1:3)	
		Model	FS	Model	FS
Drain condition	CDA	S2-CDA-M2	1,816	S3-CDA-M2	1,793
	CDB	S2-CDB-M2	1,444	S3-CDB-M2	1,444
	CDC	S2-CDC-M2	1,352	S3-CDC-M2	1,348
Load condition	CCA	S2-CCA-M2	2,086	S3-CCA-M2	2,086
	CCB	S2-CCB-M2	2,081	S3-CCB-M2	2,080
	CCC	S2-CCC-M2	2,075	S3-CCC-M2	2,075

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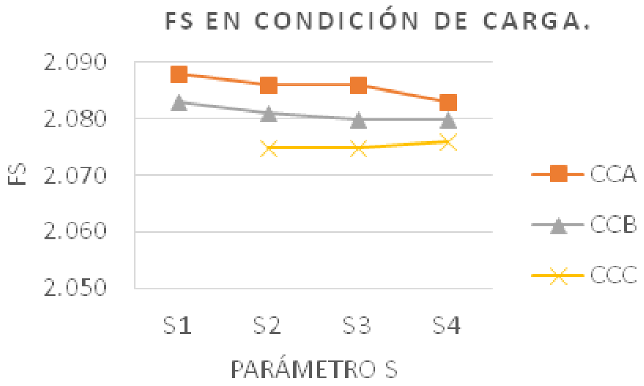
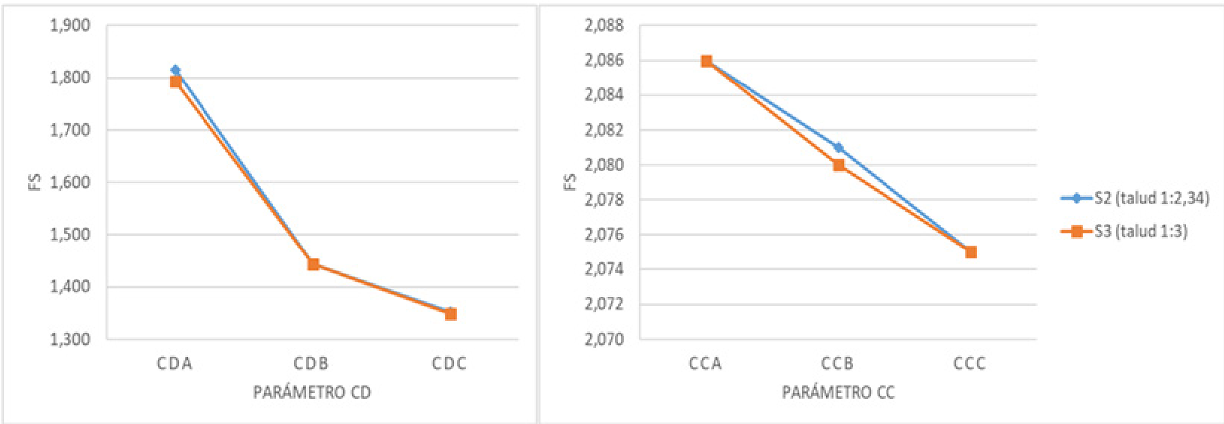


Figure 7 FS sections Model 2.

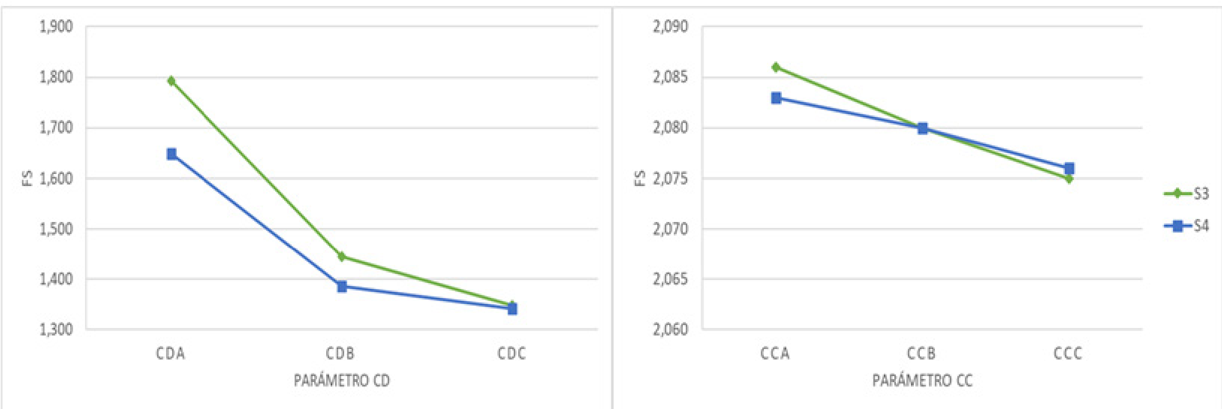
Table 7 FS of Sections 3 and 4

FS equal sections with different geometry but stored tailings.					
Condition		**S3**		**S4**	
		Model	**FS**	**Model**	**FS**
Drain condition	CDA	S3-CDA-M2	1,793	S4-CDA-M2	1,649
	CDB	S3-CDB-M2	1,444	S4-CDB-M2	1,385
	CDC	S3-CDC-M2	1,348	S4-CDC-M2	1,342
Load condition	CCA	S3-CCA-M2	2,086	S4-CCA-M2	2,083
	CCB	S3-CCB-M2	2,080	S4-CCB-M2	2,080
	CCC	S3-CCC-M2	2,075	S4-CCC-M2	2,076



(a) (b)

Figure 8 FS Sections 2 and 3 (a) Model 1; (b) Model2.



a) (b)

Figure 9 FS of Sections 3 and 4 (a) Model 1; (b) Model2.

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Conclusion

i. The features that influence the stability and security of the slopes of the tailings dam Freshwater, in decreasing order of importance, are: the presence of a surface infiltration tailings dam, position the pipe free flow conditions drainage modeled, geotechnical properties of stored tailings and varying the geometry of the dam, from project slopes.

ii. The deviation of the last built slope regarding the proposed in the original project is not a determining factor in slope stability analysis of tailings dam Agua Dulce.

iii. The viability of the closure, with respect to the analysis of slope stability of the tailings dam Agua Dulce is guaranteed under compliance with the model S3-CDA-M2, for which the tailings dam reaches the level close to the slope that was built during the operation phase, ensuring proper operation of the drain line.

iv. To improve the characteristics of the dam facing the stability and safety of their slopes after closing step is necessary to remove the condition infiltration imposed by the existence of a mirror surface water by pumping and reuse of water content and the provision of a surface drainage; corresponding to Model 2 where more than 1.9FS is ensured.

As rehabilitation plan of the area affected by the tailings dam Agua Dulce is recommended to develop the project that enables the construction of a vehicular parking after closing the dam, due to the proximity of the road Potosí-Uyuni and the burden imposed on Condition CCC guarantee analyzed under sections FS beyond what is required in the Bolivian regulations.

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None.

Conflicts of interest

The authors declare that there is no conflict of interest.

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