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Dry stacked filtered tailings: seepage behaviour during the construction process

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Abstract

In the last decade, filtered tailings deposits (FTDs) have become relevant in the mining industry because they reduce physical stability risks due to the low degree of saturation in which they work. This paper focuses on the seepage process during the construction of a conceptual dry tailings stack. The seepage process was analysed with a coupled and uncoupled model in the structural and non-structural zone of a FTD to determine the influence of variables such as density, degree of saturation, permeability, tailings disposal and interaction with the environment (precipitation) inside a dry stack. An FTD is conceptualised with a construction period of approximately 10.8 years and a rainfall regime that presents a wet season that limits the construction periods. The results show that the use of coupled seepage models determines sectors with greater thicknesses and higher degrees of saturation compared to uncoupled models. A comparative analysis is also carried out for the use of raincoats on the structural zone during the wet season. Not using a raincoat allows the generation of layers with a higher degree of saturation, which generates a heterogeneous structural zone that could have an impact on its shear strength. Finally, based on the results, guidelines are provided for geotechnical laboratory investigation plans, the adaptation of field conditions to model boundary conditions and filtered tailings disposal configurations.

Keywords: *seepage, unsaturated seepage, construction process, coupled analysis, dry stack*

1 Introduction

One of the principal challenges in the mining industry after mineral processing is the availability of the resources (e.g. water) on site for the construction and operation of tailings storage facilities (TSF). Due to the dry weather, water scarcity and community issues, as well as the mining industry's high-water consumption, efficient water use is a relevant constraint. While several methods are used to construct TSF, filtered tailings stacking is a potential alternative to overcome the constraint mentioned. The use of this method increases tailings water recovery while decreasing the risks of physical instability. The tailings achieve a lower moisture content below saturation, which means the deposits are more stable in operation and less vulnerable to seismic events, and have a lower possibility of generating acid drainage (Oldecop & Rodari 2021).

A dry tailings storage facility allows the tailings to be disposed of with a low moisture content. Therefore it is necessary to analyse the construction process of the filtered tailings from the point of view of unsaturated soil mechanics. Although it is common practice to perform analyses under the most critical conditions, such as saturation, filtered tailings storages are rarely worked in this condition. The purpose of this research is to study the variables of density, degree of saturation, permeability, tailings disposal and interaction with the environment (precipitation) in dry stack filtered tailings through numerical models that simulate a coupled and uncoupled seepage analysis (flux and strain). For this purpose, the mechanical and hydraulic properties of the tailings were estimated based on reviews of unsaturated soil from several researchers. This allowed us to determine the influence of variables such as density, degree of saturation, permeability, tailings disposal and interaction with the environment (precipitation) inside a dry stack.

2 Methodology

Stress-strain and seepage analyses, with the finite element method GEOSLOPE (2022), are used in this research to achieve a fully coupled analysis using the Sigma/W. A section of filtered tailings storage was generated according to the geometric design criteria of Cacciuttolo & Pérez (2022). Table 1 summarises the conceptual geometry used, and the model is depicted in Figure 1.

Table 1 Summary of the geometry and time of construction for a filtered tailings deposit

Parameters in model	Units	Value
Layer thickness	cm	100
Time construction by layer	Days	40
Number of Lifts	–	5
Lift height	m	10
Berm width	m	20
Maximum thickness	m	46
Total slope height	m	50
Total height	m	66
Local slope	H:V	3:1
Global	H:V	4.6:1

The model, at the bottom of the deposit, has a layer of thickness equal to 0.50 m as a simplification of the filters and drainage system. In addition, as is typical for this type of deposit, a structural zone 90 m wide and a non-structural zone have been represented. In developing the seepage analysis, seasonal fluctuations in the net precipitation throughout the year are considered as this is an important factor in the continued construction of the deposit. For numerical modelling purposes, a uniform equivalent construction ratio of 100 cm elevation increasing every 40 days has been considered; hence, the total construction time for this conceptual analysis case is approximately 10.8 years.

Two columns of a filtered tailings were analysed to simplify the behaviour of the filtered tailings deposit (FTD) in the different sectors. The first column represents the behaviour of the structural zone of the tailings deposit and has a maximum height of 26 m in 4.4 years, but the analysis continues until the end of the construction stage is reached. The second column represents the behaviour of the non-structural zone at the bottom, and the structural zone at the top of the column; the maximum height is 46 m in 7.4 years.

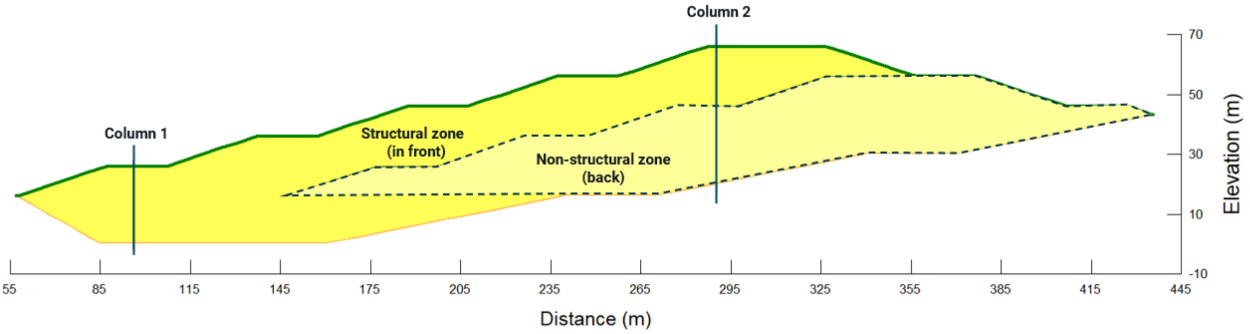


Figure 1 Conceptual geometry of an FTD

2.1 Characterisation of filtered tailings

For the development of a coupled 2D model, a characterisation of filtered tailings was carried out, with the parameters obtained being the soil-water retention curve (SWRC), hydraulic conductivity (k) and the deformability parameters (E, υ) of the tailings. For that purpose, a review of unsaturated soils laboratory tests and onsite programs from several researchers was carried out.

In the research of Gallardo et al. (2022), a laboratory test program on unsaturated tailings was executed. From this program, the SWRC for two target densities was obtained through the following methods at different suction ranges.

Gallardo et al. (2022) determined two adjustment models for the SWRC being used for his study, based on the equation of Van Genuchten (1980) for denser tailings (γ_d = 17.5 kN/m^3) and looser tailings (γ_d = 16.5 kN/m^3). The adjustment parameters are presented in Table 2 and the SWRC in Figure 3.

Table 2 Adjustment parameters for Van Genuchten model. Obtained from Gallardo et al. (2022)

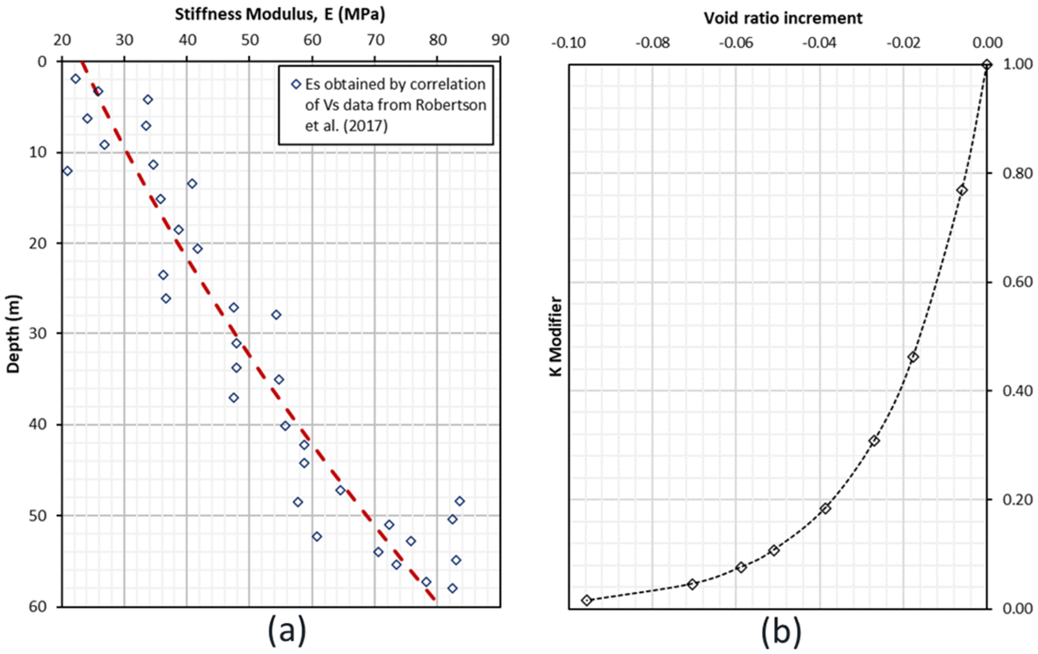
Model	Variable	γ_d = 16.5 kN/m^3	γ_d = 17.5 kN/m^3
Van Genuchten (1980)	ϴs	0.45	0.41
	ϴr	0.01	0.01
	α	8	18
	n	1.28	1.34
	m	0.24	0.24

A 1D model was used to simulate the disposition of loose and saturated tailings over compacted tailings with low moisture content. This was used to estimate the flow rate that could be seep.

On the other hand, in the study of Robertson et al. (2017), Vs values obtained in SCPTu tests on mine tailings executed onsite were used to correlate stiffness modulus (E) in depth. Figure 2 depicts the depth-dependence of the stiffness modulus. Table 3 shows the tailings properties included in the coupled analysis; all tailings were modelled as isotropic elastic.

Table 3 Material properties

Properties	Units	Saturated tailing	Unsaturated tailing	Drain
Unit weight, γ_h	kN/m^3	20.75	20.30	18.67
Moisture content, w	%	25.77	16.00	12.00
Initial void ratio, e_0	–	0.77	0.66	0.56
Specific gravity, G_s	–	2.97	2.97	2.65
Degree of saturation	%	100	71.5	56.9
Response type	–	Undrained	Undrained	Drained
Stiffness modulus, E	MPa	Figure 2	Figure 2	Figure 2
Poisson coefficient, υ	–	0.30	0.30	0.33
Maximum hydraulic conductivity-x, K	m/s	1E-07 Figure 2	1E-08 Figure 2	1E-04
Ky/Kx	–	0.1	0.1	1
SWRC	–	Figure 3	Figure 3	Figure 3



(a) (b)

Figure 2 (a) Depth-dependence of stiffness modulus; (b) Variation of void ratio and permeability

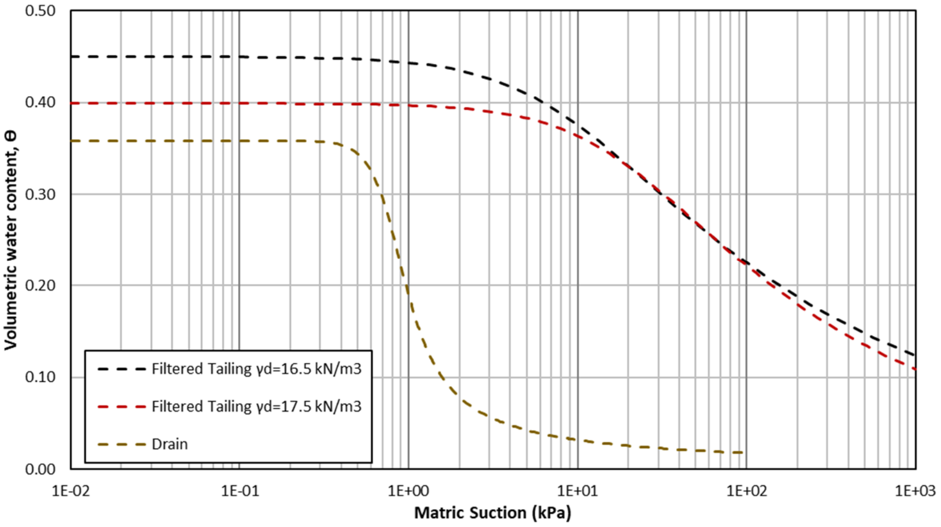


Figure 3 Soil-water retention curves from the Van Genuchten model

2.2 Hydraulic boundary conditions

The tailings are disposed of inside the FTD under specific conditions of density and moisture. However, the drying process of new layers of tailings, the environment and the self-weight consolidation of unsaturated tailings can modify the degree of saturation of the tailings. Due to grain size distribution and other factors, the tailings do not permit full seepage of precipitation. The contribution of moisture from surface flows that would reach the back of the storage and seep through the drain has not been considered in the column models; it should be evaluated in a 2D seepage model.

2.2.1 Drying platform

In accordance with the process of placing successive compacted filtered tailings layers, each layer arrives onsite with a high moisture content, so these go through the drying process. The environmental and weather conditions allow for reducing the moisture content. However, with drying time, this saturated layer generates a water flux that manages to affect the underlying compacted layers' varying moisture content (degree of saturation). This effect is evaluated through a 1D seepage model and the results are depicted in Figure 4. The model in 1D consisted of 10 m of unsaturated compacted tailings over which a 0.40 m thick loose and saturated tailings layer was added. For 2D coupled analysis, in columns one and two, it was considered a boundary condition represented by a constant value of water flux of 1.36E-08 $m^3/sec/m^2$ (approximately 1.18 mm/day) which will be added to the precipitation in the analysis scenarios where the non-structural part is used as a drying platform. For this case study analysis, a drying time of 15 days was considered to obtain the average value.

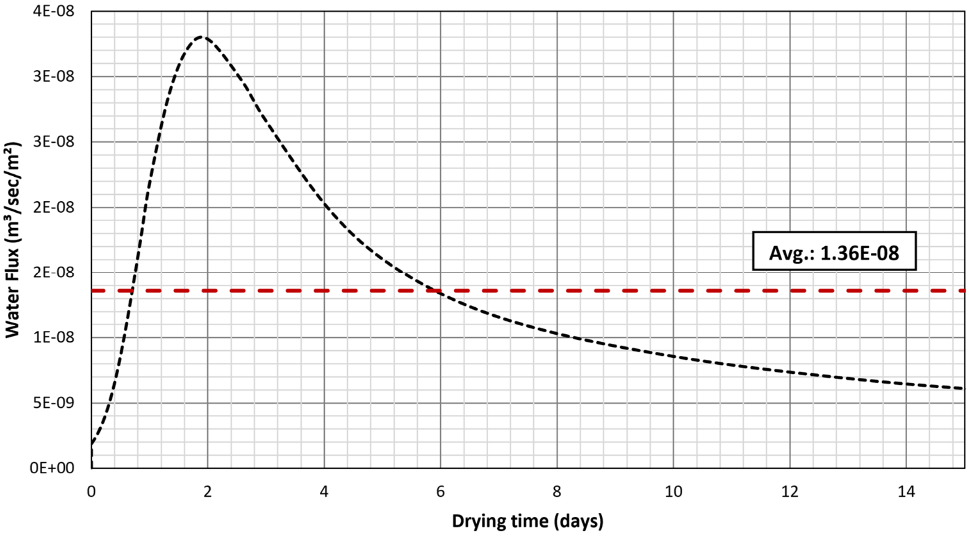


Figure 4 Water flux of saturated tailings

2.2.2 Rainfall

One of the relevant factors that affects the construction process and operational parameters in tailings disposal is the rainfall; it can stop the construction of tailings deposits until the wet season has ended and increase the moisture content of the tailings. For this research, the water flux associated with rainfall was included. Average monthly precipitation and evaporation values were obtained from the Regional Government of Apurimac (2010) study of the province of Antabamba and are depicted in Figure 5. Net precipitation values are the difference between precipitation and evaporation; those values where evaporation exceeds precipitation have been considered zero. The wet season of the year is from December to March. Some of the scenarios analysed consider that the non-structural zone is used as a drying platform on which the tailings lose moisture. For these cases, the flow determined in the previous section was added, resulting in the red line of 'Net precipitation + drying platform flow'; its effect is seen at around days 100 and also at 320.

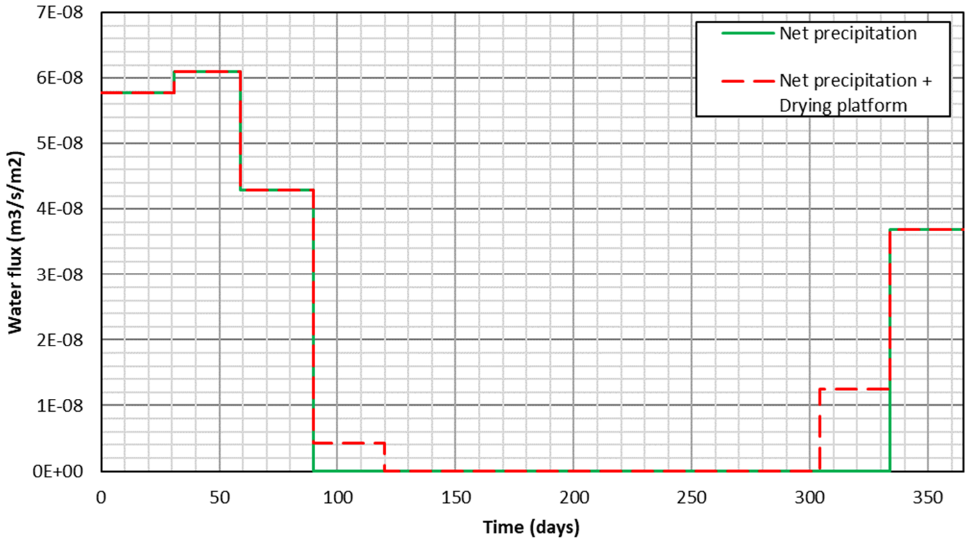


Figure 5 **Monthly water flux of the precipitation**

2.3 Scenarios of analysis

Two columns of tailings were chosen for coupled and uncoupled analysis (see Figure 1). Column 1 and column 2 are located in the structural zone and non-structural zone, respectively. With the intention of analysing the coupled behaviour of these deposits, eight scenarios were developed that take into consideration different factors including the use of a raincoat as a covering for tailings in wet seasons, variations in permeability in coupled and uncoupled analysis, the influence of boundary conditions in structural and non-structural zones, and the location of a drying platform inside or outside of the deposit. These scenarios and evaluation conditions are summarised in Table 4.

Table 4 **Summary of scenario analysis**

Scenario	Column	Raincoat	Permeability	Structural zone	Non-structural zone	Height (m)
1	Column 1	No	Constant	Net precipitation	–	26
2	Column 1	No	Variable	Net precipitation	–	26
3	Column 1	Yes	Variable	–	–	26
4	Column 2	No	Constant	Net precipitation	Net precipitation	46
5	Column 2	No	Variable	Net precipitation	Net precipitation	46
6	Column 2	Yes	Variable	–	Net precipitation	46
7	Column 2	No	Variable	Net precipitation	Net precipitation + drying platform	46
8	Column 2	Yes	Variable	–	Net precipitation + drying platform	46

As summarised in Table 4, scenarios 3, 6 and 8 contemplate the use of a raincoat during the wet season of the year so that for the wet and dry seasons of the year, the input value for the water flow was set to zero in the structural zone. In addition, scenarios 1 and 4 have constant permeability values, simulating uncoupled behaviour. Finally, scenarios 7 and 8 consider that the non-structural area of the deposit will be used as a drying platform.

3 Results

The results of the eight analysis scenarios for columns 1 and 2 are presented in Figures 6 and 7, respectively. Scenarios where the raincoat was not simulated presented layers with a high degree of saturation. This effect was marked when a coupled analysis was executed due to a reduction of the tailings permeability coefficient.

The following points are summarised below, based on the results depicted in Figure 6:

- The thicknesses of tailings layers with a high degree of saturation were greater in Scenario 2 than in Scenario 1. This is because Scenario 2 considers the reduction in permeability due to the reduction in the void ratio. This effect is higher when overburden pressure is increased.
- In Scenarios 1 and 2, tailings with a high degree of saturation were generated in wet seasons because raincoats were not simulated. On the other hand, in Scenario 3, a high degree of saturation was not reported because raincoats were used in wet seasons.
- In Scenarios 1 and 2, the last layer of tailings achieved a high degree of saturation due to a rainfall cycle that occurred after column 1 had reached its maximum height. For Scenario 3, the raincoat prevented water flux saturation of the last layer.

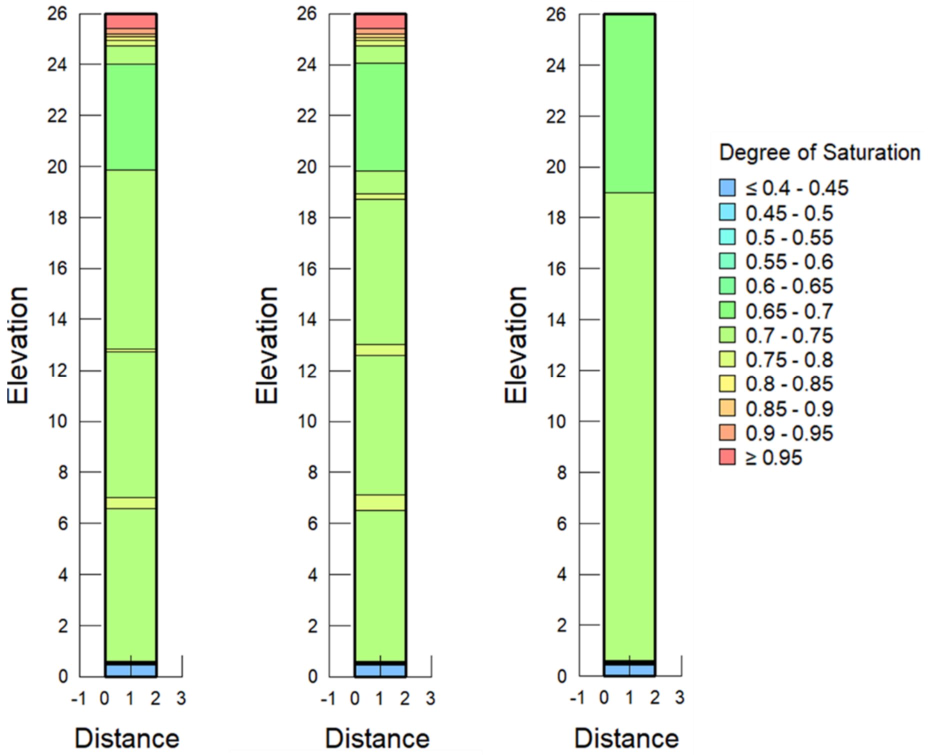


Figure 6 Results of uncoupled/coupled models in analysis of Scenarios 1, 2 and 3 (from left to right)

The following points are summarised below based on the results depict in Figure 7:

- The degree of saturation in tailings layers under high overburden pressure is greater in Scenario 5 (coupled model) than Scenario 4 (uncoupled model).
- Because the raincoat was not simulated in Scenario 4, tailings with a high degree of saturation were generated in the structural and non-structural zones during wet seasons. Alternatively, in Scenario 6, a degree of saturation has not been reported in the structural zone because the raincoat was

simulated. In the non-structural zone, the degree of saturation in tailings layers under high overburden pressure is greater in Scenario 6 than Scenario 4.

- Taking into consideration scenarios 1 and 4, the last Scenario represented several tailings layers with a high degree of saturation that increased according to depth, in comparison with Scenario 1.
- The contribution of water flux from the drying platform was represented in Scenario 7, without a raincoat, and Scenario 8, with a raincoat; obtaining tailings layers with greater thicknesses compared to those obtained in Scenarios 5, without a raincoat, and Scenario 6, with a raincoat.
- In Scenario 7, tailings with a high degree of saturation were generated in wet seasons because raincoats were not simulated. In Scenario 8, by contrast, a high degree of saturation was not reported because raincoats were used in wet seasons.

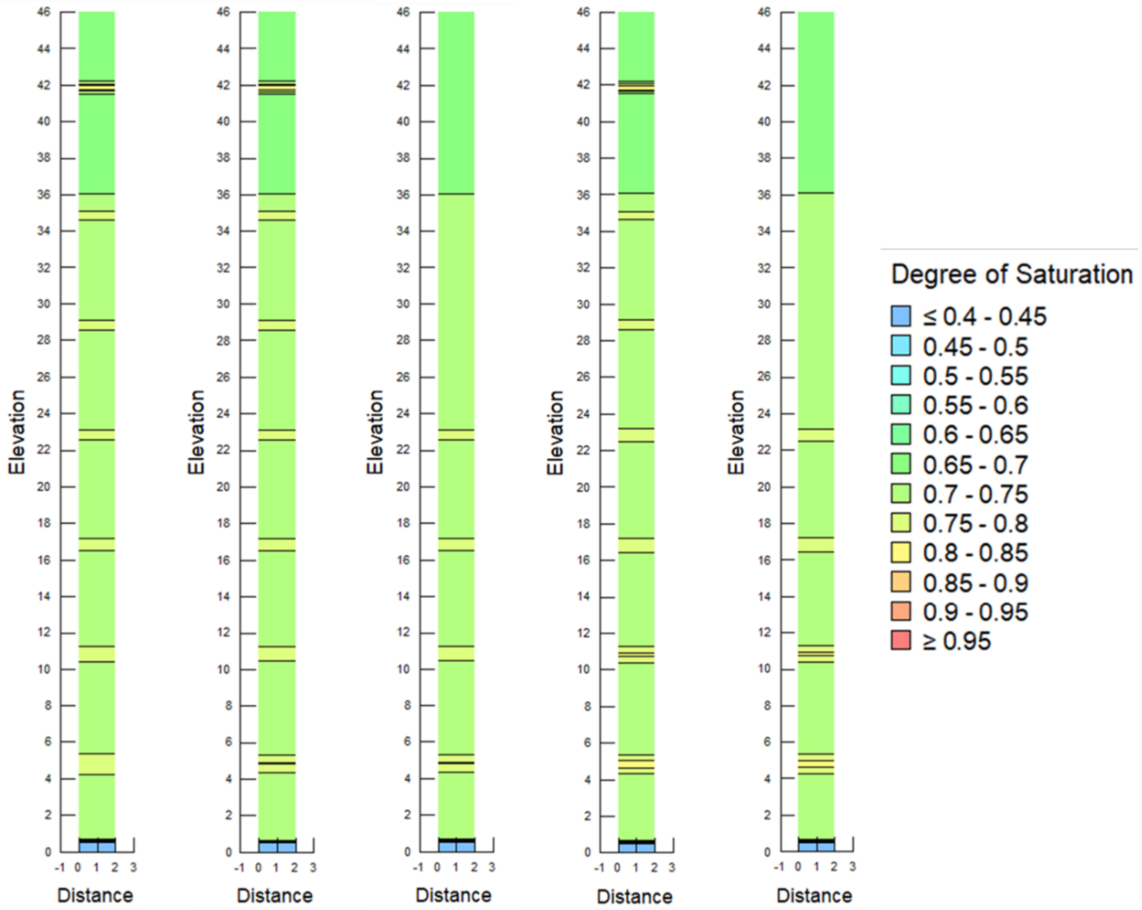


Figure 7 Results of uncoupled/coupled model in Scenario Analysis 4, 5, 6, 7 and 8. From left to right.

4 Conclusions

Seepage analyses for unsaturated tailings are usually performed with uncoupled models. However, it has been found that considering a coupled flux-strain model results in sectors with a greater degree of saturation and thickness. This is due to the densification of the tailings by self-weight which results in a reduction of the void ratio, thus reducing the permeability and increasing the degree of saturation.

Based on the shear strength of the tailings, increasing the degree of compaction would improve the strength parameters. This implies increasing the moisture content, which could reduce drying times in the field, although this would result in a higher degree of saturation.

For tailings with low permeability, horizons with a higher degree of saturation will tend to be thicker and present the behaviour of saturated materials. These horizons with a higher degree of saturation imply a loss of continuity in the strength properties of the tailings, converting it into a heterogeneous material. Although the simulation of the construction process can identify the locations with the highest degree of saturation, it should be considered that there are external factors which will impact tailings production.

Regarding the use of raincoats for the structural zone, the models that simulated their use did not present horizons of greater saturation during the wet season. However, the non-structural area of the deposit could be used as a drying platform. The moisture contribution due to this process must be evaluated for the conditions of each project. In the same way, the magnitude of the increase in the degree of saturation in the layers found in the analysis depends on the hydraulic properties of the tailings and the hydraulic boundary conditions that must be based on the operating processes of the deposit.

5 Recommendations

In the scenarios where a raincoat was not considered, layers with a high degree of saturation were generated. Their location depends on the construction process; however, the latter can be impacted by external factors and thus change the location of the saturated layers. Therefore it is recommended that physical stability analyses in static and pseudo-static conditions using anisotropic resistance models to eliminate the variability of the location of the saturated and unsaturated layers should be undertaken.

A review of investigations and literature was required to characterise the mechanical and hydraulic properties of unsaturated filtered tailings in order to achieve a coupled 2D model analysis. However, it is preferable that these parameters be obtained by laboratory testing or onsite tailings so a characterisation program focused on unsaturated soil mechanics is recommended. In addition to the typical physical properties tests (e.g. PSD, specific gravity etc.), the following tests are recommended:

- Hydraulics properties: flexible wall permeameter, SWRC for loose and compacted tailings, a drying box test and column drying test.
- Stiffness and shear strength properties: one-dimensional consolidation properties of soils using incremental loading, seepage-induced consolidation, a consolidated undrained triaxial compression test for cohesive soils, and an unconsolidated undrained triaxial compression test on cohesive soils for unsaturated and saturated conditions.

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