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Geotechnical-geochemical and operational considerations for the application of dry stacking tailings deposits – state-of-the-art

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Abstract

Filtered tailings (FT) deposition is experiencing a worldwide growing application as a potential alternative to overcome several constraints associated with land use and fresh water availability in areas near mining operations. Implementation of FT deposition can significantly reduce the volume of the tailings dam; the result is a lower impact on the project development area compared to conventional slurry and thickened tailings deposits. Furthermore, the associated costs and the physical and environmental risks, during both the overall tailings disposal operation and closure, may be significantly reduced. Water and land use can be reduced not only in arid to semiarid regions, where the FT technology is currently being applied, but also in rainy regions. A comprehensive study of the implementation of the FT technology is required because of two major issues: (1) project development areas characterised by total annual rainfall higher than 1,000 mm and seismic activity higher than 8 Mw, and (2) very fine tailings types generated in the mine process plant. These factors push geotechnical-geochemical engineering knowledge to the limit and make the industry develop novel technologies for tailings filtration and transportation to meet new necessities.

This paper presents geotechnical-geochemical considerations, including the rheological, thickening, filtering, and desiccating tailings characteristics obtained through an extensive laboratory testing program. The testing program examines a number of key parameters: the density and moisture requirements for the FT compaction, the criteria for the required area for the FT deposition for its subsequent compaction, criteria to meet the long-term physical and chemical stability during the FT disposal operation and closure, and the associated water management plan. This paper also describes experience regarding the criteria for the selection of FT equipment and transportation systems, their implementation and operation, and the operation and management of the FT deposit as a whole. Finally, future trends of FT applications associated with both the new generation of tailings filtration and transportation systems and the combined application of other tailings disposal technologies, such as the co-disposal of tailings and mine waste, are discussed.

1 Introduction

The application of filtered tailings (FT) disposal at mining operations worldwide is a potential alternative to conventional tailings disposal. This technology is an alternative that should be taken into account as part of the initial phase of a tailings disposal study. In South America, the application of FT technology at an industrial scale, in fully implemented operations with productions rates higher than 1 ktpd, started in the early 2000s in places with very different climatic conditions, i.e. from the most arid areas, with dry seasons with negligible precipitation, to mountainous areas with moderate precipitation levels of about 1,000 mm annually (Figure 1).

The main reasons for the potential application of FT to a particular site are the lack of land for tailings disposal, limited fresh water availability, and the absence of materials for the construction of the tailings dam. A better understanding of the nature of FT and the ongoing state of practice, in conjunction with the advancement of dewatering tailings technology, could make FT technology the most cost-effective alternative for disposal. Key constraints on the use of FT technology are: (1) the nature of the tailings (particle size, specific gravity, and mineralogy), which allow efficient filtration; and (2) the geomorphology of the site and the tailings production rate provide for a manageable and flexible operation. In addition, the geochemical characteristics of the tailings, associated with water quality issues during operation and closure of the deposit, play a decisive role in selecting and applying FT technology.

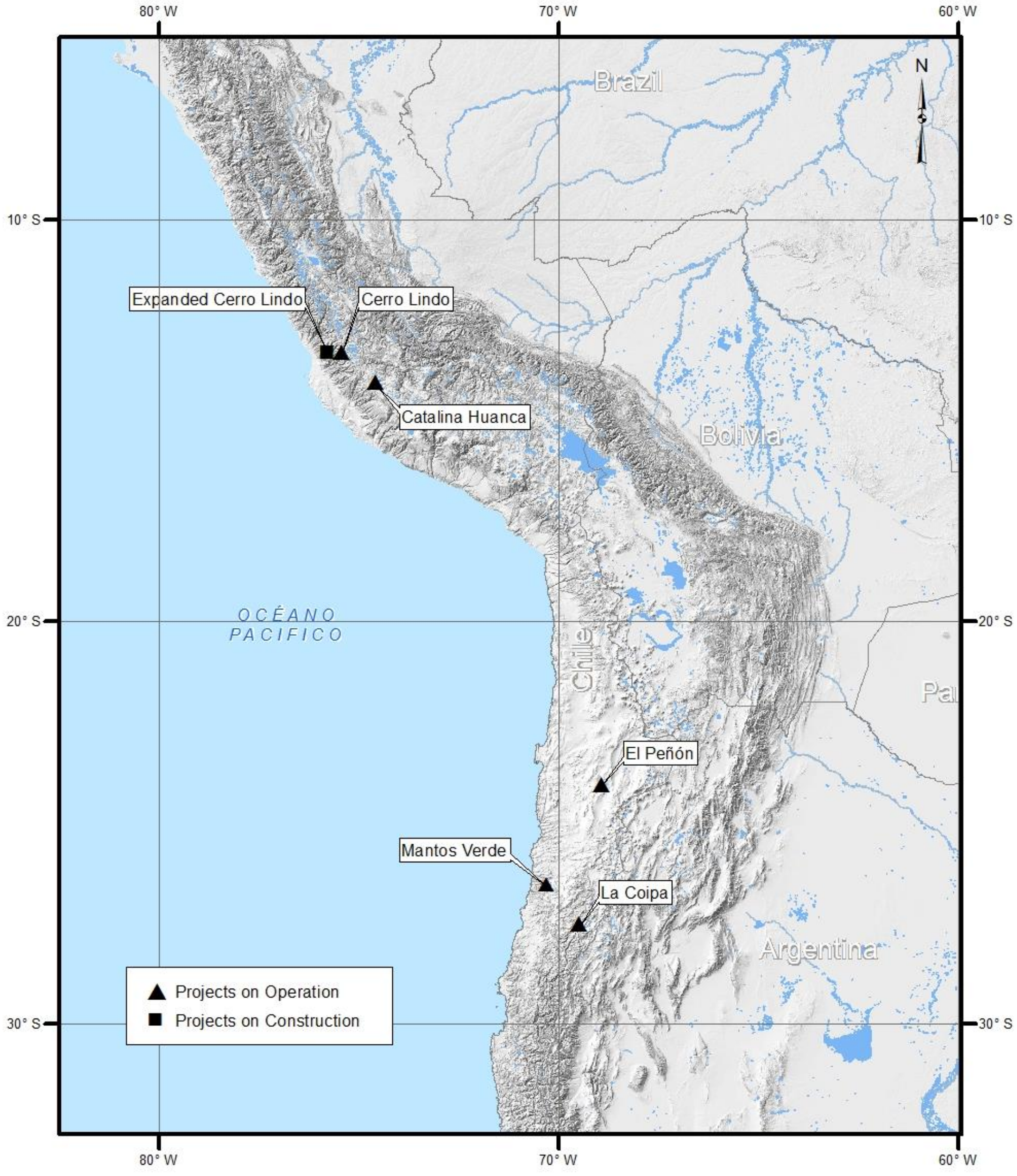

Figure 1 Location of projects employing FT in operation and in construction in South America

The first successful projects involving FT in South America were in northern Chile. This desert location has marginal precipitation, i.e. lower than 50 mm per annum, on average. In addition, this area has high seismic activity. La Coipa (18 ktpd), Mantos Verde (12 ktpd) and El Peñon (5 ktpd), the pioneering projects, were developed in the early 2000s. In all these cases, the FT were transported by either conveyors or trucks and then disposed of at tailings storage facilities (TSF); compaction was undertaken in relatively flat areas of Chile. Later, in Peru, the Cerro Lindo (15 ktpd) and Catalina Huanca (1 ktpd) projects started their FT operations in the mid-2000s. In both cases, the FT were transported by trucks and disposed of at the TSF on rugged land. An adequate in-place degree of compaction was generally achieved. From early 2008 to the present, the authors know of no record of any new FT operation with production rates higher than 1 ktpd.

Despite this fact, there is great interest among mining investors about the application of FT at a number of projects which are at the study stage.

This paper aims to contribute to the understanding of the design and operation of FT technology and methods and to describe its many advantages in contrast to conventional tailings disposal (slurry and thickened tailings). FT technology is not always the best alternative to apply at a given mining operation, but it may be applied to specific sites, tailings process types, and so on. This statement becomes relevant because, to date, FT has been applied where site conditions are difficult, i.e. high precipitation, high seismic activity, and limited containment areas.

2 Criteria for FT application

The criteria for applying FT technology for surface disposal are based on the fact that FT deposits can significantly reduce the volume of the tailings dam and reduce impacts on the project development area relative to conventional tailings. Furthermore, the associated capital and operational costs, as well as the physical and environmental risks during operation and closure, may be significantly reduced.

Both the topographic conditions and the seismic activity of the tailings facility site are relevant to a decision to compact the FT or not to compact the FT. A well compacted, self-retaining FT structure for the entire TSF is particularly necessary in areas having higher, rugged slopes (> 20%) and high seismicity (> 0.25g corresponding to a return period Tr = 475 years). On the other hand, when these site conditions are less important to the project, a hybrid alternative involving a well compacted and non-compacted FT is a choice to be taken into account (Figure 2).

When the FT deposit requires compaction, the FT moisture content at both the filter plant and that prior to in-place compaction, i.e. the target moisture content for adequate compaction, is relevant; a large difference between these two values makes FT less feasible. That is because, in order to reduce excessive water and attain the target moisture content, it is necessary to take into account the site weather conditions, particularly as they may affect the viability of drying of the tailings. At a site with higher precipitation during the year, with lower precipitation (< 50 mm monthly) during short periods, or without areas for drying of the FT, the application of FT is marginally viable. Additionally, the operational aspect is of paramount importance, since a large number of filters may be required, and this would make the FT operation less flexible and more difficult to manage.

The geochemical aspect of the FT is another major issue in the selection of an FT site. Potentially acid generating (PAG) tailings may also have a potential to leach out metals and may have a higher risk of oxygenation. Compacted FT reduces this risk of ARD in arid regions, where no water is available to transport contaminants. In contrast, in sites of moderate to high precipitation, key facilities such as sedimentation ponds, water containment, and water treatment plants may be necessary from the start of operation to closure of the tailings deposit.

The selection and the application of FT technology must take into account the costs for operation and closure; the entire FT facility has to be sustainable and environmentally friendly, with a flexible and simple operation, and adaptable to changes in the operation philosophy.

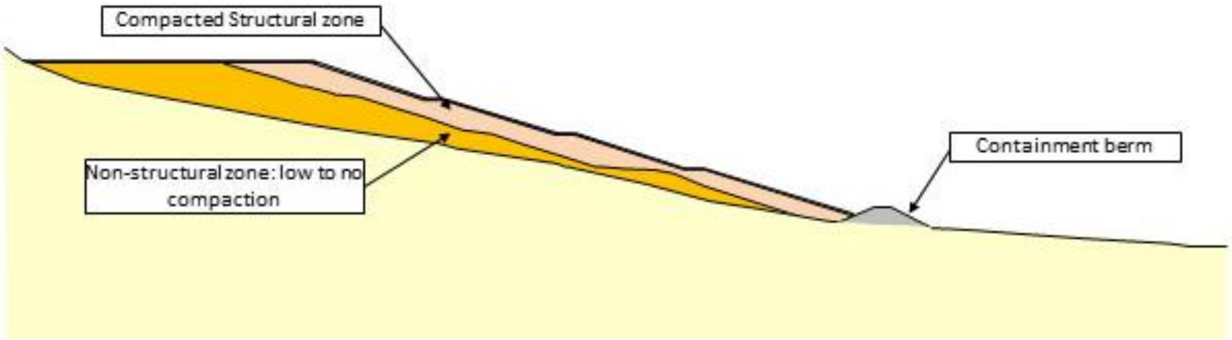

Figure 2 FT disposal cross section

3 Tailings properties and filtering

The tailings properties related to filterability are as follows:

- The particle sizes of the solids, in particular the fines content, such as clays (< 2 µ). The filter process is generally more efficient when the clay content is low.
- The mineralogy and specific gravity of the tailings. A higher value of specific gravity and lower clay and/or thixotropic minerals results in a tailings type with better characteristics for filtration.

Figure 3 shows the particle size distribution of different types of tailings in FT operations.

The filtering process determines the quality of the FT produced. The FT can be produced using mesh filters, vacuum disk filters, belt filters, and pressure filters. Pressure filters produce a much lower moisture content material by comparison with other filter types.

The effectiveness of the process is strongly influenced by the moisture content in the feed. It may be necessary to thicken prior to filtering, particularly when the tailings solid content at the concentration plant is less than 35% and the target solid content at the outlet of the filter plant is greater than 85% (Figure 4). For design purposes, laboratory testing is necessary in order to determine the efficiency of the filter systems for various solid contents, filtering pressures, types of medium, particle sizes, and so on.

Figure 5 shows the devices used in the laboratory for filtering tests: the Buckner funnel, leaf test pressure filter, and plate filter press. Figure 6 shows the resulting moisture content that it may be possible to attain given a vacuum filtration rate of 500 kg/h/m^2; this is about 22.4% and 23.8%, corresponding to two levels of vacuum. In other words, for the same tailings sample, a filter plant located at or near sea level might give higher filtration rates than one located above 4,000 masl for the same moisture content.

From the above discussion, the selection of the filters depends on the following factors:

- The target moisture content of the FT for adequate in-place compaction. If the moisture content significantly differs from the target, the weather conditions become an active factor in promoting desiccation. This process is viable in regions characterised by low precipitation. In forested regions, low precipitation can last for 3 to 4 months a year (4 to 5 months in the Andean region), while in arid regions, 10 to 12 months can be favourable for FT desiccation.
- In filtering processes working at lower filtration rates, the number of filter units installed can be significantly higher in order to meet daily production, resulting in a substantial increase in capital and operating costs.

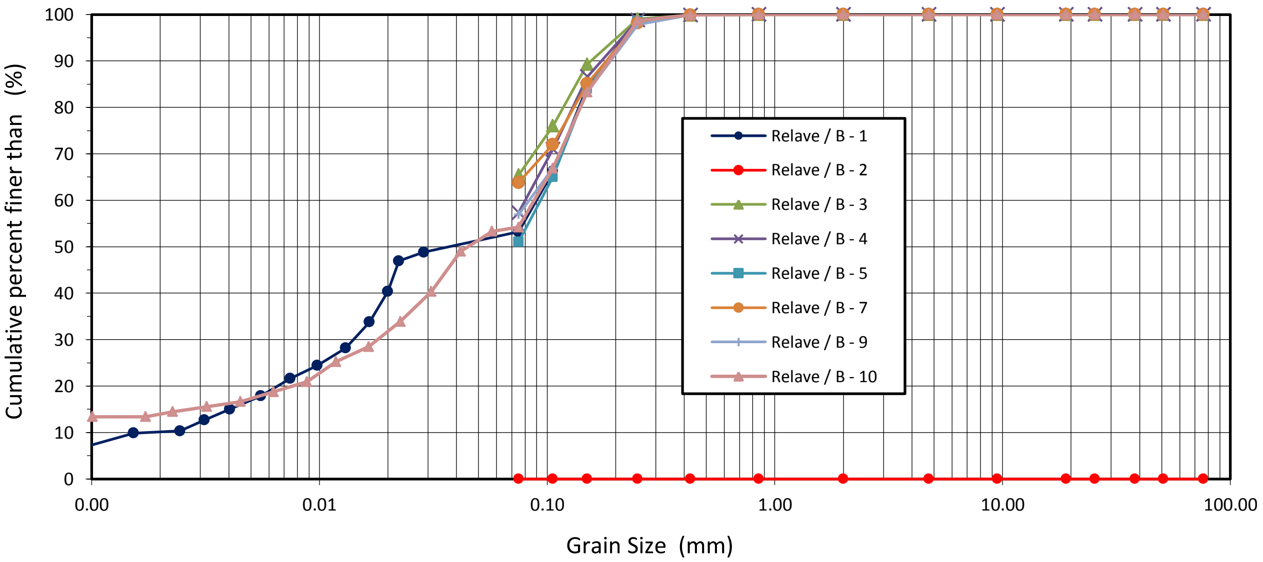

Figure 3 Particle size distribution of FT

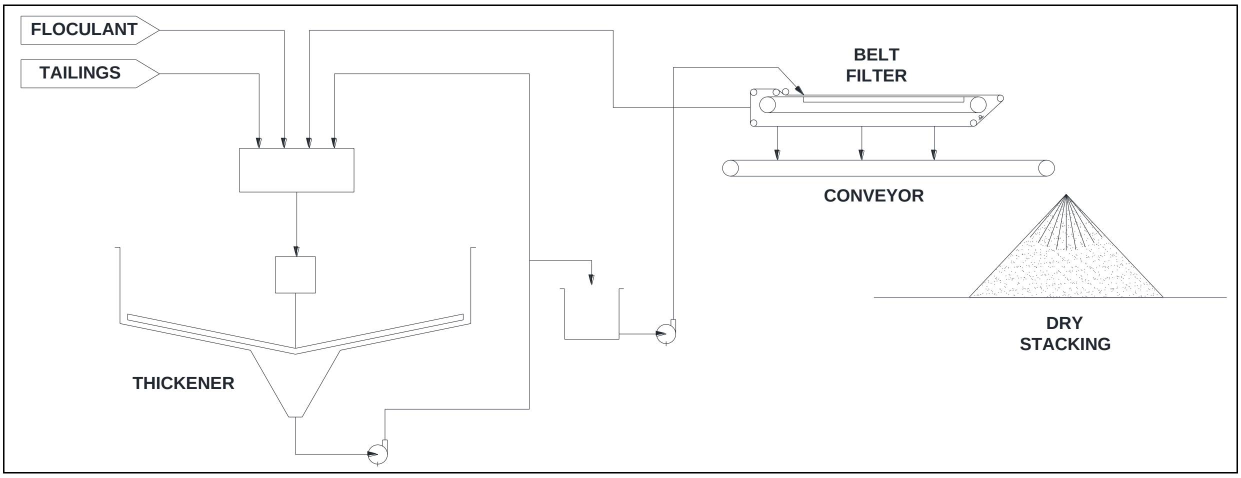

Figure 4 General flow sheet of the FT process

Figure 5 Equipment for filtering tests

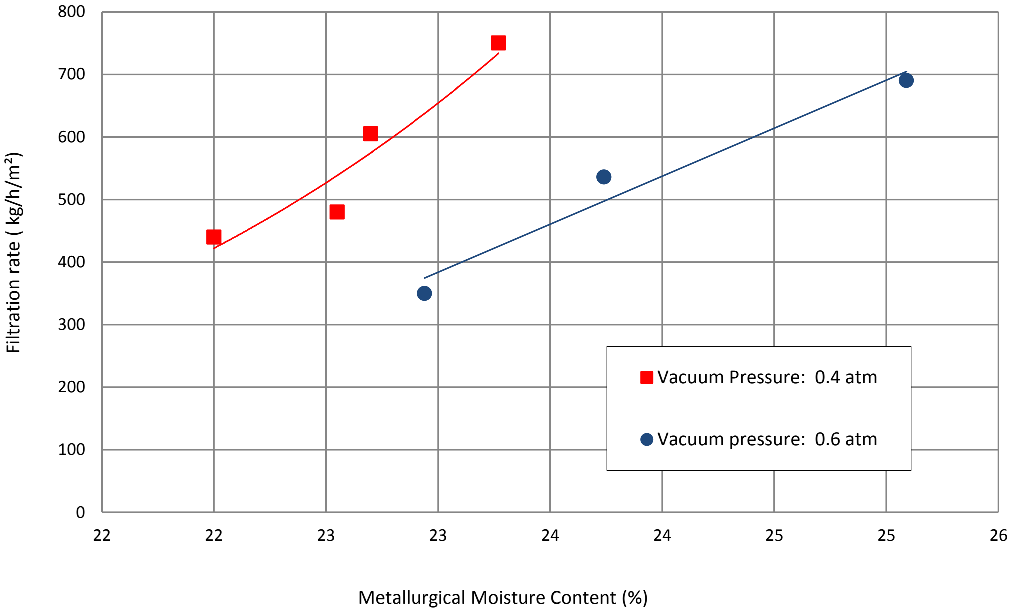

Figure 6 Filtration rate versus moisture content for different vacuum pressures

4 Dry stacking geotechnics

4.1 Determining the requirement for FT compaction

The requirement for FT compaction is associated largely with use of FT as a material to create a structural fill. For instance, compaction was particularly important for the FT dry stacking at the Cerro Lindo mine in Peru, which is located in a high seismic region (9.0 Mw) with rugged topography. The precipitation in the region is low, with less than 50 mm total precipitation monthly (Figure 7).

4.2 Determining the target range of moisture content for compaction

The FT moisture content adequate for in-place compaction is governed by the geotechnical-mineralogical characteristics of the tailings. The standard Proctor test (ASTM D 698) determines the optimum water content (OWC) and the maximum dry density (MDD) for compaction. In general, a density range of 90 to 95% of the MDD is adopted for compaction. Figure 8 shows a typical compaction curve. The criteria for FT compaction works are as follows:

- Compaction is limited by the degree of saturation of the FT. Operational experience recommends a maximum moisture content for compaction of 70 to 80% of the degree of saturation. By this restriction, FT is expected to stay well away from its saturation during the different construction stages. This is a positive factor in the physical stability of the compacted FT structure, particularly in regions with moderate to high seismic activity.
- For in-place compaction of FT, it is recommended that the FT moisture content be within the dry area of the compaction curve. This provides compaction flexibility to deal with the occurrence of low to moderate rainfall (< 10 mm).
- In a broad sense, FT compacted in the dry area of the compaction curve will result in a material having higher shear strength positive to the FT physical stability than when it is compacted with excessive water (Figure 9).

The target FT moisture content is crucial to drying the FT to a moisture content appropriate for compaction. Thus, larger drying areas may be required. As desiccation may take longer, it may depend largely on the site weather conditions.

Figure 7 View of the Cerro Lindo FT deposit – year 1 of operation (Golder, 2007)

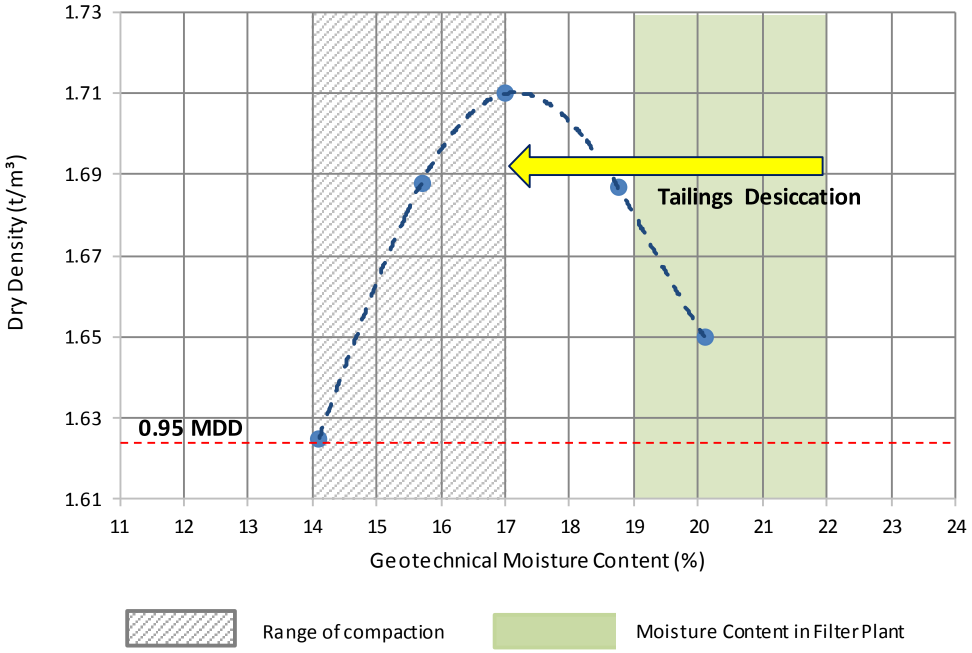

Figure 8 Typical compaction curve

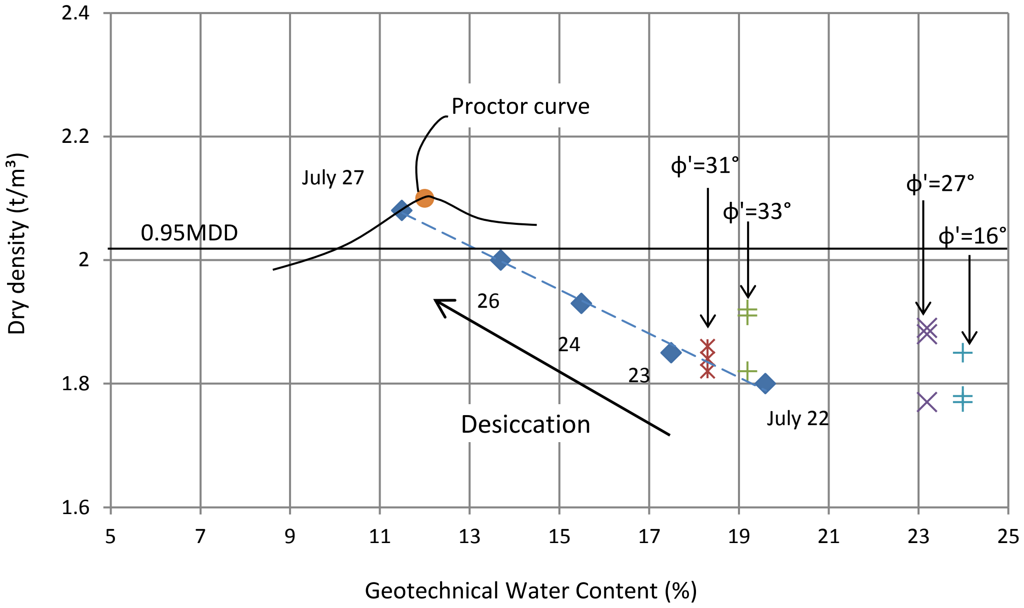

Figure 9 Variation of in-place water content-density and shear strength (Catalina Huanca Project)

4.3 Transporting filtered tailings

To facilitate FT transportation and provide for truck access over freshly deposited tailings, the moisture content discharged at the filter plant should be limited to 80% of its degree of saturation. This limitation could vary, depending on the particle size-mineralogical characteristics of the tailings. FT with moisture contents well away from the degree of saturation allow for the following:

- The stacking of the FT, thus occupying a smaller area.
- The full transportation of FT on haul trucks from the FT stacking area to the TSF without any cyclic flow induced by the truck movements or FT spillage during transportation (Figure 10).
- The provision of wider areas for truck manoeuvres for full truck transit of the deposited FT. Conveyor-stacker systems could also be considered as an option for FT transport (Figure 11).

Figure 10 Transportation – FT disposal by trucks (Cerro Lindo Project)

Figure 11 Transportation – FT disposal by conveyor-stackers (La Coipa Project)

4.4 Determining the dewatering feasibility of deposited FT

FT dewatering by desiccation becomes feasible if the weather conditions are favourable, i.e. if there is low to no precipitation. Additionally the use of mechanised equipment may help the drying process by airing. The FT production rate and time for desiccation are parameters to use in estimating the size and availability of desiccation areas.

For instance, the Cerro Lindo Project required 4.4 ha (Figure 12) to accommodate 7 ktpd of tailings and to ensure a continual field operation including discharge, stacking, and spreading; a 4-day desiccation, the preparation of a 30 cm layer, and compaction (i.e. 7 ktpd/2.11 t/m^3/0.3 cm × 4 days = 4.4 ha). Large rates of tailings production and longer times for desiccation may result in huge desiccation areas, which may not be available or operationally feasible. For instance, the Alcoa-Australia Project required more than 100 ha (Jewell and Fourie, 2006) for bauxite tailings drying.

Figure 12 Views of the discharge and drying operation of tailings (Cerro Lindo Project)

In the Peruvian Andes, desiccation is feasible during five months of low precipitation, from June to October, while a more intense precipitation, from December to April, makes FT compaction difficult. Thus, underground backfill is a disposal alternative, as with the Cerro Lindo Project. In practice, FT can continuously be compacted during continuous dry weather. Table 1 lists a number of FT operations in South America in arid climates with average precipitations below 200 mm and mean annual evaporation of 1,500 mm.

Table 1 Summary of the FT deposit characteristics under operation in South America

Project	Unit	Mantos Verde	La Coipa	El Peñon	Cerro Lindo
Location		Chile	Chile	Chile	Peru
Production	ktpd	12	18	2.6	7
Ore		Au	Au	Zn–Pb–Cu	
Transport		conveyors	conveyors	truck	truck
Type of filter		belt	belt	belt	belt
Sc	%	82–83	79–82	82–83	87–88
Classification	SUCS	SM	ML	ML	ML
%fines	%	35–40	53–55	61–65	56–58
Sg		2.67–2.69	2.76–2.78	2.60–2.62	4.0–4.2
Compaction		no	no	no	yes
Pma	mm	< 50	< 50	< 50	200
Ema	mm	>2,000	>2,000	>2,000	1,500

Where:

Sc = solid content to the discharge of the belt filter.

Sg = specific gravity.

Ema = mean annual evaporation.

5 Geotechnical stability and monitoring

The physical stability of FT deposits should be evaluated by following international standards dealing with slope stability. The FT deposit stability can be evaluated using the limit equilibrium method to establish the associated factor of safety (FS), which has to exceed the minimum FS required by the engineering practice (i.e. a FS > 1.5 for static load conditions); to meet the relevant demands of the project (i.e. higher risk in case of failure), a more comprehensive study of the FT dynamic behaviour should be considered.

The main geotechnical aspects relevant to an adequate operational management of FT deposits are as follows:

- The FT product from the filter plant should have its moisture content lower than its liquid limit (LL) to avoid cyclic mobility during transportation routines or disposal at the TSF. Figure 13 shows a FT with a solid content from 89 to 90%, a LL about 13 to 14%, and a specific gravity of 4.25; this FT is able to naturally form a conical stack. In contrast, Figure 11 shows a FT that cannot be stacked; it has a solid content from 79 to 80%, a LL from 27 to 28%, and a specific gravity of 2.77.
- Non-compacted FT is prone to undergo cyclic mobility if its moisture content is close to its LL and if mobilisation of shear stresses takes place by driving forces induced by steep beach slopes or seismic events. The Cerro Lindo FT deposit was hit by the Pisco earthquake in 2007 (7.8 Mw), and it showed no occurrence of cyclic mobility nor permanent deformation due to the FT being well compacted rather than non-compacted.

The FT deposit considers the following monitoring program (Figures 14 and 15):

- Control of the compacted layer thickness.
- Control of in-place moisture content and density of the compacted layer.
- Control of gradation and specific gravity of the material.
- Strength and moisture content verified at depths through standard penetration tests (SPT).
- Control of the level and underground water quality beneath the tailings deposition area.
- Overall slope control of the tailings deposit.

Table 2 shows a summary of the above-mentioned controls (Cerro Lindo Project).

Table 2 Summary of geotechnical and water quality controls

Type of control	Unit	Value	Control frequency
Layer thickness	Cm	30–35	Per compacted layer
Compacting moisture	%	5–7	Per compacted layer
In situ dry density	t/m^3	2.7–2.8	Per compacted layer
Gradation	–	ML	Monthly
Specific gravity	–	4.0–4.2	Monthly
Strength with depth	Nspt	20–40	Annually
Moisture with depth	%	6–8	Annually
Depth of underground water level	m	>40	Monthly
Overall slope of the tailings deposit	H:V	2.8:1	Annually

Figure 13 Filtered tailings with moisture content < 85% LL

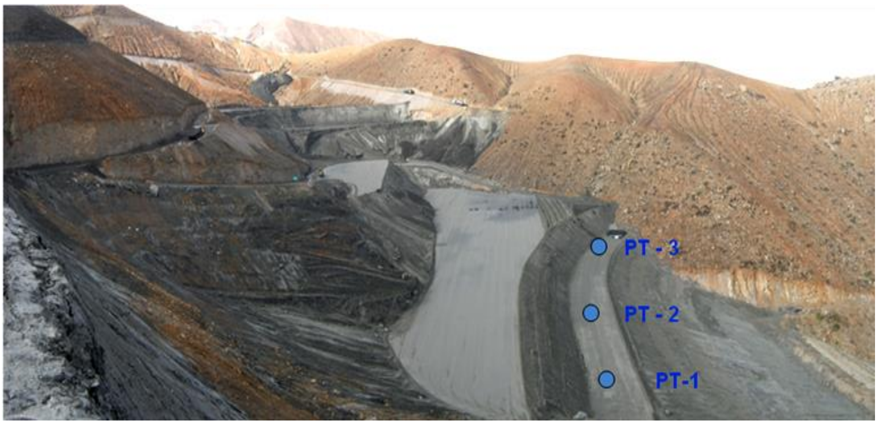

Figure 14 View of the installation points of Casagrande type piezometers, SPT tests and moisture in depth

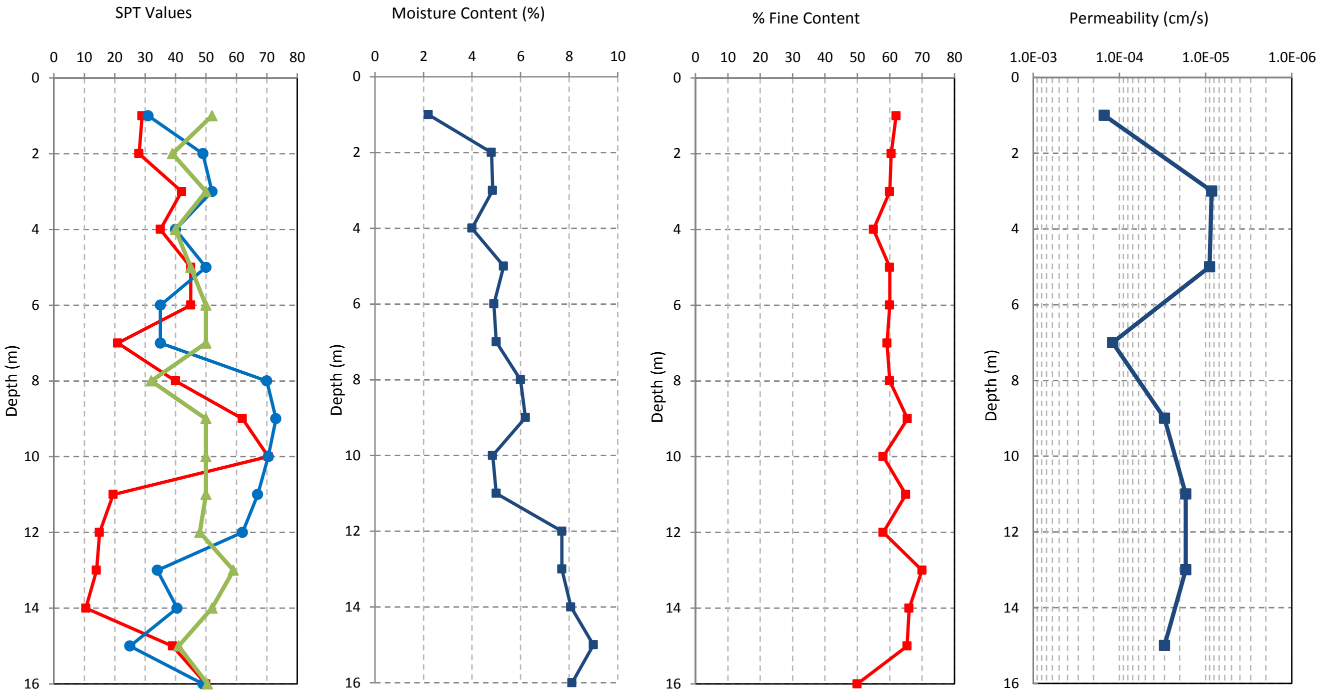

Figure 15 Typical results from the monitoring program (Cerro Lindo Project)

6 Geochemical stability

The geochemical characteristics of the tailings play a key role in FT. PAG and leaching metal tailings are limitations for disposal, particularly in rainy regions where metals may leach to the environment if no water collection systems or water treatment plants are implemented. This restriction becomes less relevant if PAG tailings are disposed of in arid regions and the groundwater level is deeper.

If FT is to meet structural functions, it needs its moisture content to be well away from the degree of saturation. This condition promotes oxygen infiltration into the tailings, resulting in a decrease of geochemical stability. Compaction works can reduce tailings permeability, decreasing oxygen infiltration.

7 Discussion

Filtered tailings (FT) has become a widely used alternative method of tailings disposal in the last decade, especially in sites with low water availability and restraints on site containment. In South America, at least five successful operations are known: La Coipa, Mantos Verde, and El Peñon projects, located in Chile, and the Cerro Lindo and Catalina Huanca projects, located in Peru. These operations have shown many advantages in contrast to the conventional tailings disposal. This has encouraged mining operators to consider FT in a number of projects in regions with harsh conditions, i.e. high precipitation and high seismicity, and even to consider its use with tailings more difficult to filter.

Compaction is important to FT deposit, and this requires achieving physical stability. The moisture content is a key parameter for adequate FT in-place compaction. In this context, FT with low moisture content can be attained by filtering and desiccating on site. To dewater tailings more effectively, the industry is developing more efficient filtering systems, i.e. vacuum and press filters, which are capable of generating drier tailings. In general, the implementation of FT can significantly reduce the volume of tailings dams, resulting in reduced impacts upon the project area and reduced costs during operation and closure in contrast with conventional disposal, e.g. the Cerro Lindo Project.

8 Future trends

In general, FT generation needs a tailings thickening process prior to filtration in order to enhance the filtration rates; in this sense, filtering is becoming a more popular concept.

When a project demands tailings compaction, this can be attained under marginal precipitation, i.e. three to five months, and the tailings may be disposed of as slurry or thickened tailings the rest of the year.

Where both a paste plant and an FT process are employed, underground backfilling work can be scheduled in rainy periods, while during the dry season, tailings can be disposed on surface by dry stacking.

The co-disposal of tailings and waste rock is becoming more accepted in countries like Peru, where waste rock from an open pit to ore is significantly higher than 2:1 (waste: ore). Considering current high prices of minerals, the waste/ore is increasing, generating more mine waste rock. The geotechnical and geochemical characteristics of both streams could be advantageous for co-disposal, particularly when waste rock has high neutralisation potential and the tailings stream is non-PAG.

Acknowledgements

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