Drying and wetting cycles in tailings dams: effects on physical, mechanical and hydraulic properties

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ABSTRACT

The study examines the drying and wetting cycles of tailings dams (TDs) and their impact on physical, mechanical and hydraulic properties. TDs are divided in four zones: the dike, the discharge zone, the transition zone and the distal zone (also known as the decantation pond). The filling process of the tailings dam involves five phases: 1) dumping and wetting, (2) segregation, (3) sedimentation, (4) consolidation, and (5) drying. The occurrence of drying and wetting cycles depends on the water balance, which can be expressed as Inflow = Outflow ± Storage Coefficient. These cycles are influenced by factors such as changes in the discharge point within TD dike and reservoir, weather conditions, and other external factors. The analysis of drying and wetting cycles in TDs reveals several trends: (a) grain size, density, internal friction angle, and permeability decrease from the discharge zone toward the decantation pond and (b) porosity, fine particle content (particle less than 75 microns), plasticity, cohesion, and capillarity height increase as we move toward the decanting lagoon. Despite these findings, there is currently no established methodology for managing the filling process or controlling wetting and drying cycles of TDs.

Keywords: tailings dams, water balance, properties

1. Introduction

Tailings dams (TDs) constructed using the hydraulic filling method exhibit four distinct zones (Figure 1a-d): Z1: dike/dam, Z2: discharge or beach zone, Z3: transition zone and Z4: distal zone or decantation pond/lagoon. The distribution of these zones depends on two factors: (1) the type of TD (e.g. upstreaam, centerline, modified centerline, downstream – Fig. 1a-d), and (2) the location and number of the tailings discharge points. Throughout their existence (in perpetuity!), TDs undergo various geological and geotechnical processes influenced by both external and internal earth dynamics (Fig. 1) (Rodriguez-Pacheco et al. 2021). Among these processes, wetting and drying cycles play a significant role (Fig. 2). These cycles are regulated by the water balance within the dam, as described by Eq. (1) (Zandarin et al. 2009), (Garino et al. 2021).

$$W_{in} = W_{out} + S_{coeff} \tag{1}$$

where W_{in} is a water inflow, W_{out} is a water outflow and S_{coeff} is a water storage coefficient of the dam.

An overview of the significant processes and phenomena that affect TDs is shown in (Fig. 1a). (Rodriguez-Pacheco et al. 2021) and (Zandarin, et al. 2009) provide a comprehensive conceptual model and detailed explanation of these factors. Wetting processes have been extensively studied by researchers in various investigations (Zandarin et al. 2009), (Garino et

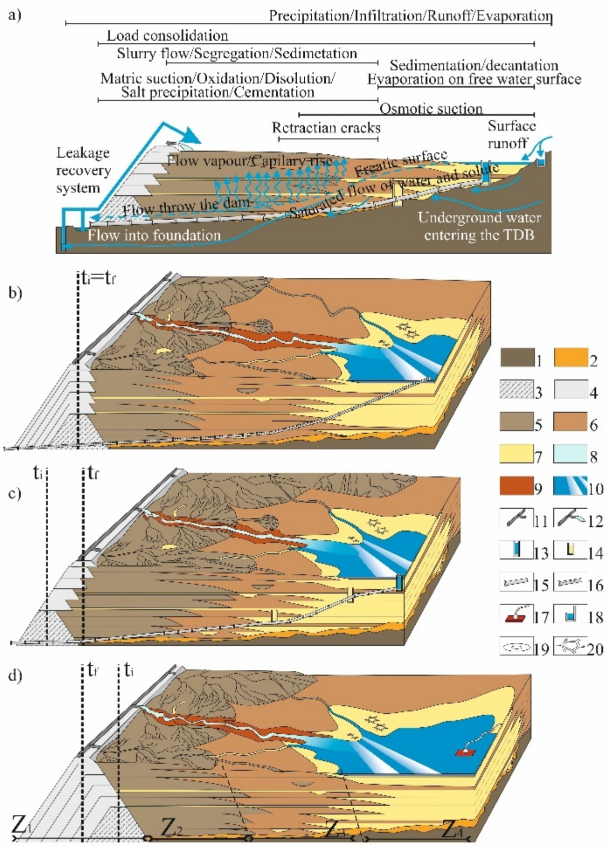

Figure 1. a) Upstream, b) centerline, c) modified centerline, d) downstream, ti) initial position of the dike, tf) final position of the dike, 1) foundation, 2) alluvial, 3) starter dike, 4) rising embankment, 5) discharge zone with coarse

sand, 6) transition zone with fine sand - silts, 7) distant zone with silts - clay , 8) current discharge, 9) paliochannel, 10) decanting pond, 11) inactive dumping point (spigot), 12) dumping point (spigot) activo, 13) decanting tower

al. 2021), while ongoing research is dedicated to developing techniques for determining particle size in tailings (Caparrós 2017), (Rodriguez 2002, 2006) and (Rodriguez et al. 2004, 2007). Moreover, the drying processes and crack formation in tailings are currently being investigates in different regions across the globe (Rodriguez-Pacheco 2021), (Garino Lobardi et al. 2021), (Caparrós 2017), (Rodriguez 2002, 2006), (Rodriguez et al. 2004, 2007), (Blight 1994, 1997) and (Wels et al. 2003).

The wetting cycles of the TD basin (Fig. 1a) are regulated by various factors, including:

1. the conditions of tailings discharge and the solid-liquid ratio,
2. weather conditions such as precipitations and snowmelt,
3. inflow of water from surface runoff,
4. water seeping into the foundation,
5. input of water from mining operations, such as slurry from water treatment facility,
6. pumping and discharge of drainage water to the dam
7. adjusting the position of the decanting lagoon and
8. malfunctioning in the drainage system.

The TD´s drying cycles are regulated by the water outflows, including:

1. evaporation,
2. drainage,
3. pumping to the facility or another reservoir,
4. flow through the dam dike and
5. flow to the foundation (Fig. 1a).

The aim of this study is to demonstrate how TD wetting and drying cycles impact physical, mechanical and hydraulic properties, along with the spatiotemporal changes in these cycles.

1.1. Methodology

In this work we analyze the variation of physical, mechanical and hydraulic properties obtained from laboratory and in-situ testing. We will show the results from various TDs constructed by the hydraulic backfill method.

The drying and wetting surfaces were observed by examining satellite images taken at different time steps. The laser diffraction method was used for granulometric analysis (Rodriguez 2002), (Caparrós 2017). The guidelines provided in (Rodriguez 2002, 2006) were used to assess the saturated hydraulic permeability. The mechanical strength characteristics were determined using methods outlined in (Rodriguez 2002), (Rodriguez et al. 2007) and (Rodriguez-Pacheco 2021).

2. Results

2.1. Stages of TDs wetting and drying cycles

Through the analysis of images (Fig. 2) and (Fig. 3), observations in the field (Fig. 4), in-situ testing as well as laboratory experiments, it is possible to establish the phases or steps involved in the drying and wetting cycles of TDs.

1. Dumping and wetting. Tailings that have been dumped contain a water content of 70-60% by volume. The discharge can occur at one specific point or simultaneously at multiple points (Fig 1) and (Fig.2). The subsequent stages are determined by the type of discharge, the volume, the intensity, and the method employed. The speed of tailings runoff is influenced by whether the discharge is aerial od subaerial. The wetting process occurs when water enters the dam through various pathways, with the most common being the change in discharge point. It has been observed that the ratio of liquid to solid content affects the segregation stage (Rodriguez-Pacheco et al. 2004, 2021), (Blight 1994, 1997). Furthermore, the magnitude of the discharge impacts the thickness of the layers that will develop within the decanting basin forming the TD (Fig. 4a-b1). Additionally, it leads to the alternation of coarse and fine materials (Fig. 4b1).
2. Segregation. After being released, the tailings move along the beach from the discharge point (Fig. 1) and (Fig. 2). During this process, the larger sand particles settle down through sedimentation. When the solid content is below 40%, natural sorting usually takes place. The segregation is influenced by the size and density of the solid particles in relation to the distance they travel (Rodriguez-Pacheco et al. 2021), (Blight 1994). The portion rich in silt settles in the transition zone. The finer clay-sized particles ultimately settle beneath the water table in the decantation lagoon (Dobry et al. 1967), (Beral 1976), (Wels et al. 2003) and (Rodriguez-Pacheco et al. 2021).
3. Sedimentation: when flowing along the beach and the transition zone, the solid particles settle and are classified by size (Rodriguez-Pacheco et al. 2021), (Blight 1994, 1997). The water with the very fine particles and colloids in suspension escapes as surface runoff into the lagoon. At this stage, coarse tailings (sands) lose more than 50% of the water they initially contained. In contrast, silt-clay-sized tailings lose only 20-30%. The very fine tailings that settle in the settling pond do not lose water at all. In situ and experimental studies show that this stage lasts between 1 to 4 days (Blight 1994, 1997), (Rodriguez 2006), (Rodriguez et al. 2004, 2007) and (Rodriguez-Pacheco et al. 2021). In the settling pond and the water-covered zone, sedimentation takes place by settling. In the flooded zone the depth of the water table plays an important role. In the flooded zone

the precipitation of solids occurs by the action of the force of gravity and the density of solid particles (Rodriguez-Pacheco et al. 2021). Recent studies show that the process of dumping and drying of tailings in laboratory columns has different stages (Garino et al, 2021), (Rodriguez-Pacheco et al. 2022) and this process results in stratification with slope angles from 0.5 to 3.0 degrees.

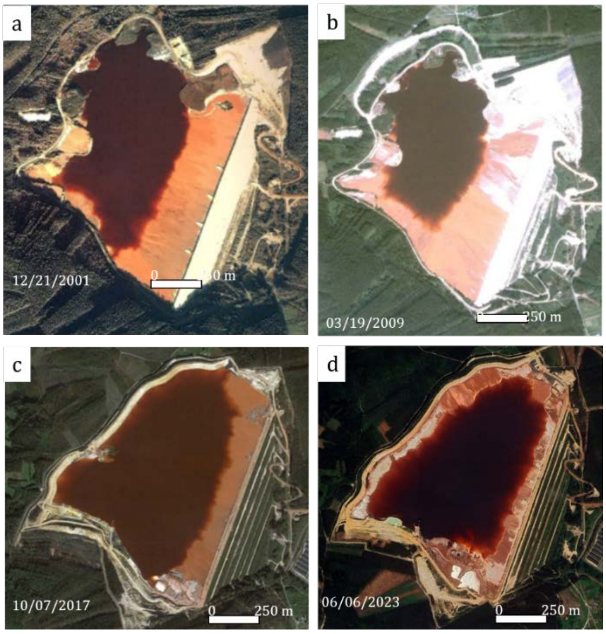

Figure 2. Spatiotemporal evolution of an aluminium tailings dam, San Ciprián, Galicia, Spain. Height > 70 m (after Roberto-Pacheco et al. 2021)

4. Consolidation refers to the stage when the solid particles in the tailings come into contact and the pore volume starts to decrease due to self-weight (Blight 1994, 1997), (Rodriguez et al. 2004), (Rodriguez-Pacheco 2021, 2022), (Garino et al 2021). This stage, which can last anywhere from 1 to 14 weeks, involves the expulsion of pore water to the surface, lower layers, and lateral layers of the tailings. Coarse tailings, which are primarily composed of sands, experience a water content reduction of 10-15% during this stage (Wels et al. 2003). On the other hand, fine silt-clay tailings drain a slightly larger amount of water compared to coarse tailings due to their higher porosity and compressibility. As a result, they retain more than 40-50% of their initial water content at the end of consolidation (Berzal 1976), (Wels et al. 2003), (Rodriguez-Pacheco et al. 2021). In the discharge and transition zones, the tailings achieve a solid structure during this stage. It is worth noting that the consolidation process is influenced by internal geodynamics, particularly when tailings undergo cyclic shearing, i.e. tailings subjected to cyclic shearing always consolidate (Rodriguez-Pacheco et al. 2021). Studies conducted on abandoned dams in semi-arid climates have revealed that the consolidation of tailings within the TD is a slow process (Garino et al. 2017). Furthermore, it has been observed that areas of tailings dams can remain fully saturated even 50 years after abandonment (Oldecoop et al. 2011), (Garino et al. 2017), (Garino 2018).
5. The drying process occurs when the tailings discharge point is relocated, causing the surface of the tailings to gradually dry out (Fig. 1) and (Fig. 2) (Berzal 1976), (Wels et al. 2003), (Oldecop et al. 2006), (Rodriguez-Pacheco et al. 2021, 2022), (Garino et al. 2021), Initially, water evaporates from the surface, starting with the free water (Rodriguez-Pacheco et al. 2021), (Garino 2017), (Garino et al. 2021). Once the tailings are no longer saturated, the drying stage begins. The rate of evaporation is influenced by various factors including weather conditions, grain size, density, mineralogical composition, and pore water hydrochemistry. In theory, this stage can continue indefinitely until a state of equilibrium with atmospheric conditions is achieved. However, the duration of the tailings drying period is limited by factors such as the operating rate of the tailings disposal system, growth rate, climate, and drainage system, etc. (Oldecop et al. 2006), (Rodriguez-Pacheco et al. 2021, 2022), (Garino et al. 2021). Once the discharge cycle returns to the starting point, the consolidated, unsaturated, and cracked tailings will become wet again (Rodriguez 2002), (Oldecop et al. 2006), (Rodriguez-Pacheco et al. 2021), Additionally, groundwater and the movement of the flooded surface can also impact the extent of drying that the tailings undergo (Fig. 2) as well as capillary rise from the water table (Oldecop et al. 2006), (Garino et al. 2021), (Rodriguez-Pacheco 2021). In a study conducted by (Wells et al. 2003), it was found that the moisture content in the coarse tailings from a copper mine decreased to 9% of its initial value after one month of drying, whereas the fine tailings retained 40% of their initial moisture.

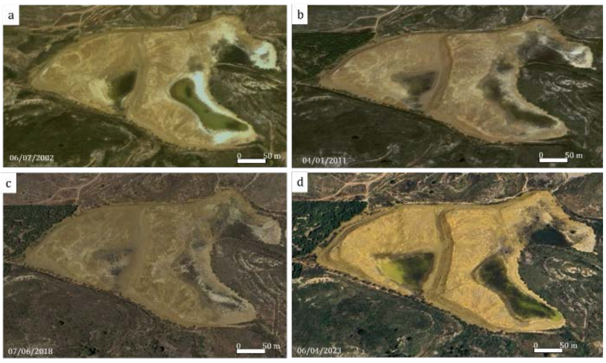

Figure 3. Spatiotemporal evolution of the drying and wetting cycles of an abandoned tailings dam, Escombreras, Cartagena-La Unión mining district, Murcia, Spain. The tailings are from Pb-Zn mining. The white color represents precipitation of sulfate salts.

Other research on the drying process of tailings, specially those derived from Ni (nickel) extraction (Rodriguez-Pacheco et al. 2021) and Pb-Zn (lead-zinc) mining (Garino 2018), (Garino et al. 2021), has identifies three different stages (explained further). Experimental investigations have also revealed that the drying process can be inhibited by the formation of salt precipitates on the surface (Garino 2018), (Garino et al. 2021), (Rodriguez-àcheco et al. 2021, 2022).

Desiccation cracks are formed when the drying process reaches areas containing fine materials, as depicted in Fig. 4c. The extent and size of these shrinkage cracks are influenced by the type of tailings and the thickness of the dump layers. Additionally, the area affected is determined by the thickness of the strata and the type of the material. These cracks significantly enhance the permeability of the porous medium, increasing it by one to two orders of magnitude (Wells et al. 2003). Furthermore, they also contribute to the anisotropy of the porous medium.

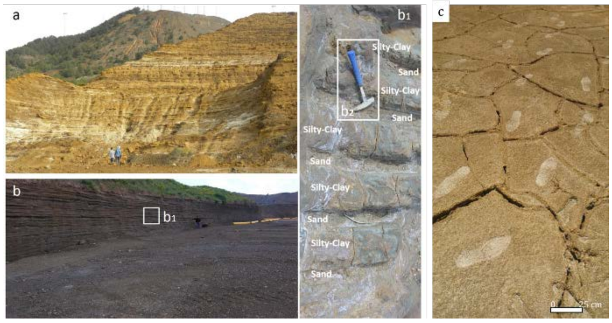

Figure 4. (a) Layering at the face of an abandoned tailings dam (El Descargador, La Unión, Murcia, Spain), (b) a profile of a cut in a tailings dam during its withdrawal, (b1) detail of the layering and cracks, (b2) detail of the thickness of the layers and (c) view of desiccation cracks on the lagoon surface. The tailings are from Pb-Zn mining.

Various experimental works (Wels et al. 2003), (Garino et al. 2021), (Rodriguez-Pacheco et al. 2021, 2022) have extensively examined the drying and wetting cycles. In (Rodriguez-Pacheco et al. 2022), a study outlines five distinct stages from discharge to the development of desiccation cracks, while (Rodriguez et al. 2007) delves into the numerical simulation of the drying process and crack formation observed in the laboratory. The saturation process following unsaturated tailings is explored in (Rodriguez-Pacheco 2023), and it has been observed that repeated wetting and drying cycles lead to the consolidation of tailings, as discussed in (Rodriguez 2002, 2006). This consolidation is attributed to their open structure, significant initial porosity, stratification, and cracking. The drying and crack formation of tailings have also been the focus of numerical modeling to comprehend the coupled phenomena governing these processes, as highlighted in (Swarbrick 1992), (Rodriguez-Pacheco 2023).

The tailings drying process consists of three stages according to (Garino 2018), (Garino et al. 2021), (Rodriguez-Pacheco et al. 2021): initial stage, intermediate stage and residual stage. These studies have been carried out for a single drying process from saturated tailings samples, simulating the initial discharge in columns of different characteristics.

a) Initial stage: the evaporation front coincides with the tailings surface and the degree of saturation in the tailings is constant throughout the stage ($S_r = 1$).
b) Intermediate stage: the evaporation rate decreases, if atmospheric conditions (relative humidity, solar radiation and wind speed) cause evaporation to exceed the capillary rise capacity, the suction on the ground will exceed the amount of air entering the tailings and the liquid phase will lose continuity. Consequently, the evaporation front will move downward into the vertical profile of the tailings and vapor flow will begin to be generated. This stage usually lasts longer than the initial stage, but is still transient.
c) Residual (or low evaporation rate stage): the atmospheric factors that favoured evaporation have less influence and, therefore, evaporation decreases. The key factor is matric suction and, in some cases, osmotic suction (Garino 2018), (Garino et al. 2021), (Rodriguez-Pacheco et al. 2021), especially in dams derived from the flotation process. At this stage, the evaporated flux is limited by the flow produced by the capillary rise from the water table to the evaporation front. The capillary fringe defines the position of the evaporation front, which is different for each type of tailings and in each tailings dam zone.

The spatiotemporal variation of the drying and wetting cycles of the operational tailing dam are illustrated in (Fig. 2) while (Fig.3) shows similar variation in an abandoned TD. Both dams have a specific area that remain submerged in water consistently. However, the difference between active and abandoned TDs is that in the latter the water enters only from climatic conditions (rainfall, snowmelt), possible subsurface seepage from the foundation, surface run off and malfunctioning of the drainage system. In the active TD there are many more factors, as was described in the introduction (Rodriguez et al. 2007).

2.2. Effect of wetting and drying cycles on the physical properties of tailings

2.2.1. Effect on particle size distribution

Vertical profile of the spatial variation of the grain size of the sedimented tailings from the dike to the decanting pond are shown in (Fig. 5). Throughout the analysis we refer to the size of the solid particles. It can be seen that the predominant fraction is sand with an average value close to 85% by weight (Fig. 5a) and the silt fraction increases with the depth. This is due to the fact that the dam was built by the upstream method (Fig. 1a), (Fig.2 – Fig. 4). Fig. 5b is the discharge or beach zone where the sand fraction also predominates with an average of 63%. In this zone the behavior is more irregular. Fig. 5c represents the transition zone where the silt fraction predominates. The sand fraction is fine sand with an average of 15%. Fig. 5d shows the profile of the decanting lagoon zone. The predominant fraction is silt, followed by clay-sized particles. Fine sands barely reach 5%.

Scanning electron microscope image of particle from the discharge zone can be seen in (Fig. 6). The particles are highly irregular, very angular with a lot of edges and some elongation that is not detectable with magnifying glass.

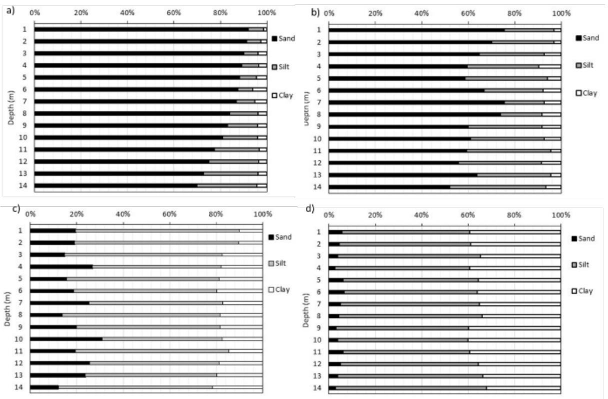

Figure 5. Variation of grain size within the tailings dams in a vertical sounding in each of the TD zones, a) dike, b) discharge, c) transition and d) decanting pond.

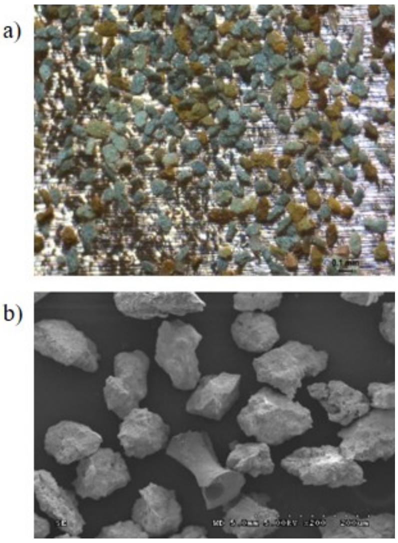

Figure 6. a) Magnifying glass and (b) scanning electron microscope images of particles from the discharge zone

2.2.2. Effect on void ratio and porosity.

The void ratio and porosity of the tailings stored in the dam is conditioned by the drying process (Rodriguez 2006), (Rodriguez et al. 2007), formation of desiccation cracks and by the consolidation due to increase load caused by the discharge of new tailings. This influence is clearly observed in the variation of permeability inside the tailings dam (Fig 7a). The loosest material is found to be in the lagoon zone with the high void ratio and decreasing its value while approaching the discharge zone.

2.3. Effect of wetting and drying cycles on the mechanical properties of tailings

In (Fig 7ab) can be clearly seen how the drying processes condition the strength of the samples in the vertical profile. The shear strength parameters are controlled by the position of the lagoon and its capacity to dry and drain.

The spikes of higher resistance (Fig. 7c- Fig.7e) are due to periods when greatest drying occurred. This effect decreases from the discharge zone towards the lagoon. Note that the difference between the lagoon zone and the discharge zone is greater than one order of magnitude. The resistance in the lagoon zone is the lowest of all. This low value in the lagoon is due to the fact that the tailings have never dried out and therefore they never fully consolidate.

Fig. 8 illustrates the results of the resistance parameters such as internal friction angle (φ). The highest values of the φ correspond to the discharge zone, decreasing its value in the direction of the decanting pond. This is conditioned by several factors (1) coarse material, mostly sandy, (2) the discharge zone is where the most intense drying processes take place and (3) it is the zone with the best drainage, etc.

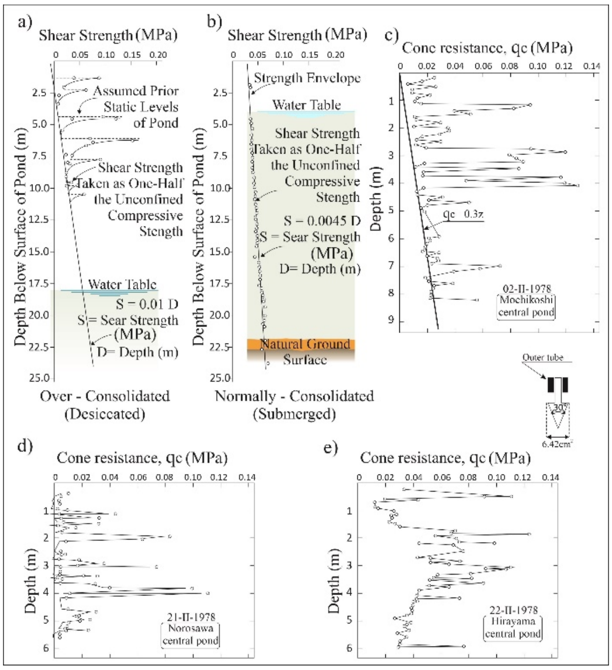

Figure 7. Changes in shear strength due to (a) drying and (b) wetting cycle (modified after (Smith 1969)) and (c), (d), (e) cone resistance in the three different TDs central ponds

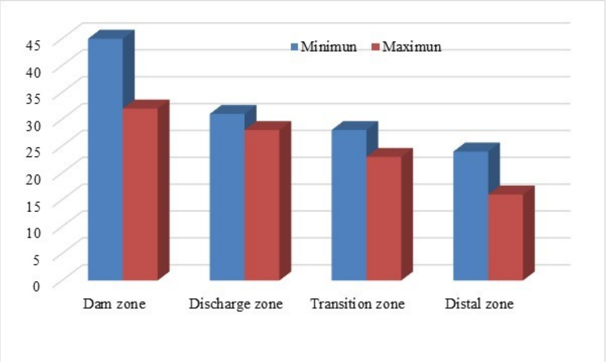

Figure 8. Internal friction angle measured in different zones

Shear wave velocity in tailings has significant implications for their behavior. (Fig. 9) shows the variation of the shear velocity with the distance from the discharge zone measured for six different TDs. It can be observed that, in all six cases, v_s gradually decreases while approaching distal zone (Z_4). Hence, tailings with low shear wave velocity are more susceptible to liquefaction during for example seismic events-Moreover, low v_s indicates that the material is relatively soft or weak in terms of its ability to transmit shear stress.

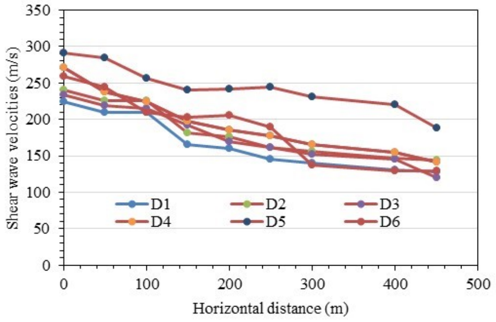

Figure 9. Shear wave velocity measured for six different TDs

2.4. Effect of wetting and drying cycles on the hydraulic properties of tailings

Figure 10a shows the relation between void ratio and saturated permeability from the different zones of the TD. The permeability varies by an order of magnitude between zones. There is some linear correlation between the permeability value and the void ratio. Fig 10b shows the change in permeability in relation to the discharge point. At a distance of 300 metres the saturated permeability decreases by more than two orders of magnitude. These results are consistent with other studies (Blight 1995), (Garino 2018), (Garino et al. 2021), (Rodriguez-Pacheco et al. 2021).

The variation of capillary height to the distance to the discharge points is shown in (Fig. 11). The capillary height has been calculated as follow:

$$h_c = \frac{2T_S}{\gamma_W e D_{10}} \tag{2}$$

Where T_s is the surface tension of water at ambient temperature (=0.0742 N/m), γ_w is the density of water, e is a void ratio and D_{10} is the size of the sieve that allows 10% by weight of the material to pass through.

It can be seen capillary height increases by more than an order of magnitude between discharge point and the decanting lagoon.

3. Conclusions

Fully understanding the effect of drying and wetting cycles on the characteristics of tailings is crucial to guarantee safety and stability of tailings dams. To explore the effect of the wetting and drying cycles on the physical, mechanical and hydraulic properties of the tailings, laboratory, in situ testing were carried out.

Based on the above study, the following conclusions can be drawn:

1. the occurrence of wetting and drying cycles is regulated by water balance within the dam,
2. exist four well defined zones (dike/dam, discharge zone, transition zone and decanting pond) within TD with high variation in material properties,

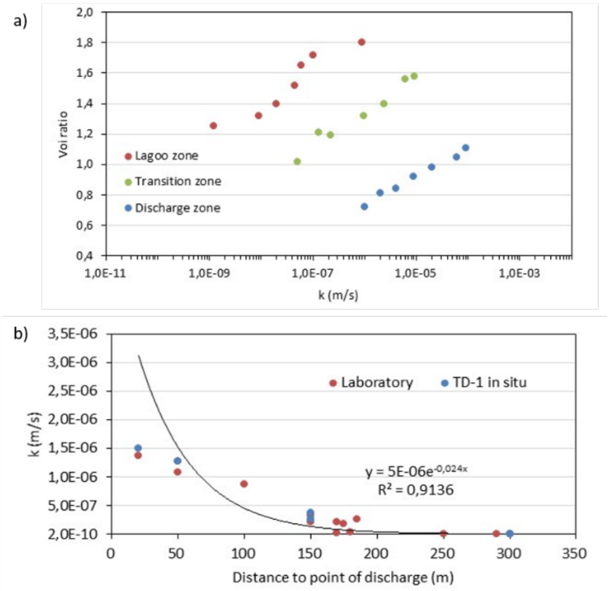

Figure 10. Saturated permeability effect with: (a) void ratio for different TD zones and (b) distance from the discharge point

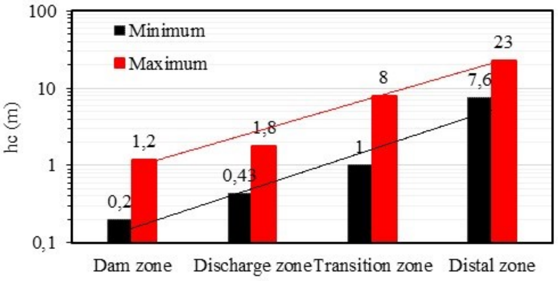

Figure 11. Variation of capillary rise in different zones of tailing dam basin (after Rodriguez-Pacheco et al. 2021).

3. process of drying can be limited by precipitation of salts on the TD surface.
4. non-operating TDs can stay saturated even decades after their abandonment, that may lead to dam failure,
5. drying of the tailings increase its density, uniaxial compressive strength, tensile strength, and decrease the pore pressure and the capillary height,
6. the resistance parameters abruptly decrease when the saturation exceeds 80%
7. the variation of permeability in relation to the discharge point can be more than two orders of magnitude (zones that are difficult to drain)
8. low values of v_s indicate that material is weak and prone to liquify,
9. the highest values of interparticle friction angle were measured at the discharge zone (coarse material, best drainage and possibility to dry),
10. high capillary rise limit drying (existence of water that cannot be drained)

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References

Berzal J.L. 1976 “Presas de residuos mineros.” Revista de Obras Públicas 123, pp.301–333, 1976. ([in Spanish])

Bligth G.E. 1994 “The master profile for hydraulic fill tailing beaches.” Proc. Instn. Civ. Engng, 107, pp. 27-40, 1994.

Blight G.E. 1997 “Interactions between the atmosphere and the Earth.” Geotechnique 47(4), pp. 715–767, 1997.

, 2021. https://doi.org/10.1680/jgeen.21.00109

Caparrós A.V. 2017 Rheology of Pb-Zn post-flotation wastes in the Sierra de Cartagena-La Unión (SE Spain). PhD Diss, Polytechnic University of Cartagena, Spain. https://doi.org/10.31428/10317/7012

Dobry R., Alvarez L. 1967 “Seismic failures of Chilean tailings dam.” J Soil Mech Found Div 93, pp.237–260, 1967.

Garino L.M., Rodari G. and Oldecop L. 2017. “Characterization of mine waste materials after 50 years of climate interaction” Second Pan-American Conference on Unsaturated Soils, Dallas, United States, 2017.

Garino L.M. 2018 “Estudio delo comportamiento mecánico e hidráulico de depósitos de residuos mineros ubicados en zonas áridas”. Ph.D. Thesis, University of San Juan USJ, Argentina, 2018.

Garino L.M., Oldecop L.A., Romero Morales E.E., and Rodriguez-Pacheco R.L. 2021 “Tailings desiccation process studied in environmental chamber experiment.” Proceedings of the Institution of Civil Engineers – Geotechnical Engineering, 1-11, 2021

Oldecop L., Garino L.M., Muñoz J.J., Rodríguez R. and García C. 2011. “Unsaturated behavior of mine tailings in low precipitation areas.” In Unsaturated Soils (Alonso E and Gens A (eds)). Taylor & Francis, London, UK, pp. 1425–1430, 2011. https://doi.org/10.13140/RG.2.1.4660.7527

Oldecop L., Rodríguez R. 2006 “Estabilidad y seguridad de depósitos de residuos mineros.” In: Rodríguez R, García-Cortés A (eds) Los residuos minero metalúrgicos en el medio ambiente. IGME, Madrid, pp. 197–243. www.researchgate.net/publi catio n/26374 7187 (in Spanish)

Rodríguez R. 2002 Estudio experimental de flujo y transporte de cromo, níquel y ranganeso en residuos de la zona minera de Moa, Cuba: Influencia del comportamiento hidromecánico,” Ph.D. Thesis, Technical University of Catalonia UPC, Barcelona, Spain, 2002.

Rodríguez R., Candela L., Lloret A. 2004 “Experimental system for studying the hydromechanical behaviour of porous media.” Vadose Zone J 4, pp. 345–353, 2004. https://doi.org/10.2136/vzj2004.0105

Rodríguez R. 2006 “Hydrogeotechnical characterization of a metallurgical waste.” Can Geotech J, 43, pp. 1042–1060, 2006. https://doi.org/10.1139/t06-061

Rodríguez R., Sánchez M., Ledesma A., Lloret, A. “Experimental and numerical analysis of desiccation of a mining waste.” Can Geotech J 44, pp. 644–658, 2007. https://doi.org/10.1139/t07-016

Rodríguez-Pacheco R, Muñoz-Moreno A, Caparrós A.V., García-García C, Brime-Barrios A, Arranz-González J.C., Rodríguez-Gómez V., Fernández-Naranjo F.J., Alcolea A. 2021. “How to prevent Flow Failures in Tailings Dams.” Mine Water and the Environment. 40, pp. 83-112, 2021. https://doi.org/10.1007/s10230-021-00752-8

Rodríguez-Pacheco R., Brime A., Gascó G., Pérez-Jodra C., Martín-Martínez A., García-García C., Méndez A. 2022 “Experimental study of efflorescence salt crusts formation in tailings dams: Possibility of metal recovery.” Minerals Engineering 185, 2022. https://doi.org/10.1016/j.mineng.2022.107673

Rodríguez-Pacheco R. 2023 “Automatic System for the Study the Interaction Between Porous Media and Atmosphere” Clime Change and Environmental Conditions. https://doi.org/10.20944/preprints202311.0211.v1

Smith E.S. 1969 “Tailings disposal and liquefaction.” T Soc Min Eng (AIME) 244, PP.179–187, 1969.

Swarbrick, G.E. and Fell, R. “Modelling desiccating behaviour of mine tailings.” J. Geotech. Eng. ASCE. 1992,118, 540–557, 1992.

Wels C., Robertson A., Mac G. 2003 “Conceptual model for estimating water recovery in tailings.” In Proceedings of the 10th International Conference on Tailings and Mine Waste, Vail, Colorado, USA, 12-15 October, 2003, pp. 87-94, 2003

. Zandarín M.T., Oldecop L.A., Rodríguez R., Zabala F. 2009 “The role of capillary water in the stability of tailing dams.” Eng Geol 105, pp. 108–118, 2009. https://doi.org/10.1016/j.engge o.2008.12.003