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How high is too high? Challenges on the next generation of dewatered tailings stacks

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Abstract

Building on the experience of successful smaller-scale dewatered tailings stack operations with production rates of up to 35,000 tpd, filter-pressed tailings stacking is being considered as a technically and economically viable alternative of dewatered tailings management for even higher production rates, pushing 50,000 to 100,000 tpd, involving intensive earthworks operations and intricate construction sequencing plans.

The need to establish dewatered tailings solutions as a sound business option for large-scale projects in water-stressed nations like Chile and Mexico is motivated by water (the lack of availability, rising cost of water and sustainable water use) but also by dam safety, lowering the risk profile of the large conventional tailings storage facility portfolios.

This paper will present the fundamental aspects of the design and operation of dewatered stacks based on practical planning and operational experience. This will ultimately provide some guidance on "how high is too high?" in the context of critical state soil mechanics and other relevant geotechnical aspects and a case study providing some reference on the planning of a dewatered stack.

Keywords: *dewatered, stack, critical state, liquefaction, strain softening, brittle, filtration, tailings, compaction, height*

1 Introduction

Dewatering and stacking of tailings is motivated by the potential to reduce footprint, limit the environmental impact potential of metal leaching and acid rock drainage, optimise water availability, and enhance the tailings storage facility (TSF) safety profile.

Recent studies have detected the possibility of water stress and predictions are not encouraging. Figure 1 summarises the water stress areas anticipated globally by 2040, highlighting the mining hubs for key metallic commodities (Morgan & Dobson 2020; Delevingne et al. 2020). Water usage is increasingly a crucial factor in mining operations in water-stressed areas in accordance with the environmental, social and governance (ESG) commitments. Due to limitations on the use and availability of groundwater, or the distance to alternative water sources (e.g. desalinisation plants), there has been a rise in the price of water in some mine operations, reaching up to USD 9/m^3. Recent trade-off studies conducted in these regions by SRK Consulting (SRK) indicated that the cost of shutting down operations or reducing production to meet water availability could outweigh the cost of building dewatering plants.

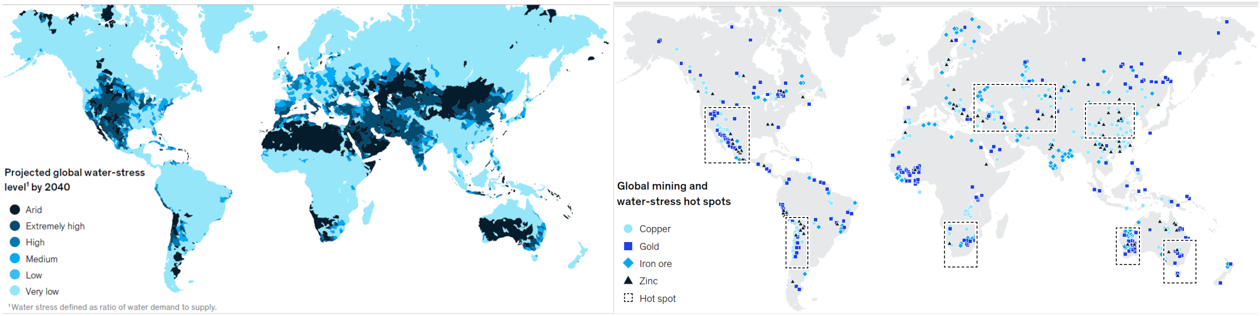


Figure 1 **Projected global water scarcity map by 2040, where southern USA, Mexico and northern Chile mining regions are expected to be arid or under an extremely high water stress (Delevingne et al. 2020)**

In recent years, a few trials and pilots have been conducted to advance the filtration technologies for use in operations with higher throughputs (up to 50,000 tpd). More recently, operations with very high throughputs (>100,000 tpd) are pushing the limits of dewatering and stacking technologies. An example of this is the copper mines in the north of Chile, which have struggled for decades with water availability and portfolios of large-scale cycloned-sand TSFs with potential high consequences (Norambuena et al. 2019).

This paper presents a conceptual framework to flag potential geotechnical risks that practitioners might encounter during the design, deposition planning and operation of large-scale dewatered tailings stack operations. The framework is based on SRK's recent experiences in smaller-scale dry stack operations in Mexico, Colombia and Guatemala, as well as early-stage studies for larger-scale operations in Chile.

2 Soil mechanics: the theoretical minimum

Stacking dewatered tailings can lower the risk profile for the entire facility. The denser and homogeneously placed material lowers the risk of slope failure and lowers the amount of free and interstitial water that could provide flowability in the event of a breach. However, due to the material's contractiveness, a stack may still undergo undesirable deformations and even flow failures if it is not constructed according to the design intent or is incompatible with the anticipated loading.

This section will explore some geotechnical concepts that are relevant for the design and operation of a dewatered tailings stack using test results from a case study to provide practical experiences and examples.

2.1 Critical state soil mechanics considerations

Much like conventional slurry-based tailings facilities, the framework for global stability of the dewatered stacks requires consensus in aspects on soil mechanics, particularly on critical state soil mechanics (CSSM). CSSM can be used to assess soil under a specific in situ density and under specific confining stresses: whether contractive (i.e. susceptible to liquefaction if saturated) or dilative (i.e. minor or not susceptible to liquefaction). Based on lab testing and case studies supporting flow slides in sands and silts, Shuttle & Cunning (2008) proposed the boundary of the contractive and dilative region as the $\psi = -0.05$ offset from the critical state line (CSL). Figure 2 shows in the CSL for Velardeña Mine tailings (Norambuena et al. 2021) on the e-ln p′ space.

If the in situ state of dewatered tailings is loose after placement, it will likely land in the red zone, meaning it is susceptible to liquefaction if saturated. If the dewatered tailings were placed in a dense condition, it will land on the blue zone, where liquefaction is unlikely.

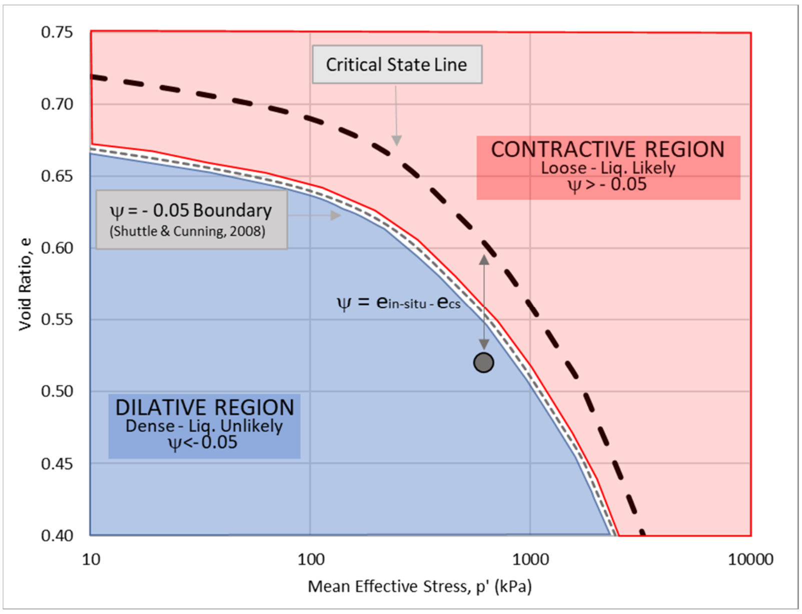
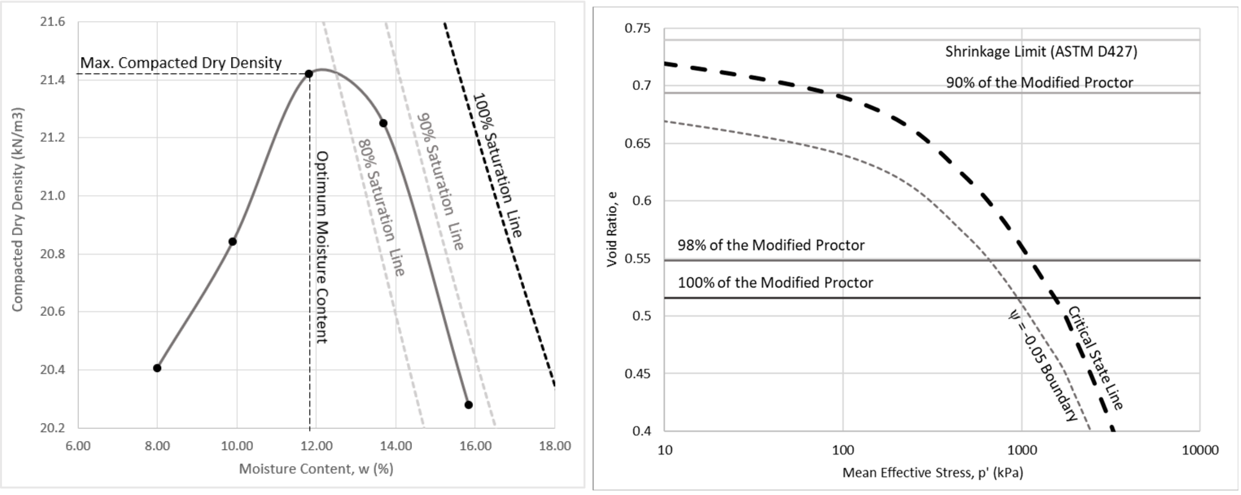


Figure 2 **Definition around critical state line and whether the in situ state is susceptible to liquefaction because it is looser than CSL or non-susceptible to liquefaction because it is denser than CSL**

2.2 Compaction of dewatered tailings

When building an earthen structure, applying stress and energy (e.g. weight and vibration) to the placed material can increase its density, especially if heavy compaction and relatively thin layers are used. According to CSSM, the increase of density due to compaction of the dewatered tailings could allow the in situ state to shift towards the dilative region, mitigating the susceptibility to liquefaction.

The standard and modified Proctor tests (ASTM 2021d and ASTM 2021c, respectively) are laboratory-scale tests used to assess the mechanics of compaction of granular materials and define the highest density that could be achieved either as standard Proctor maximum dry density (SPMDD) or modified Proctor maximum dry density (MPMDD) with the optimum gravimetric geotechnical moisture content (OMC). Figure 3a shows the result of a modified Proctor test on a tailings sample of Velardeña.



(a) (b)

Figure 3 **(a) Compaction curve from a modified Proctor test identifying the maximum compacted dry density achievable and the OMC; (b) The CSL and different fractions of the MPMDD**

Proctor compaction tests help define the compaction specifications informing the objective moisture content that eases the process of reaching a high density with compaction equipment. Usually, a fraction of the SPMDD or MPMDD is specified for construction, together with a moisture content within a range of the OMC. Figure 3b shows the CSL of the case study overlapped with the different target degrees of compaction from the modified Proctor shown in Figure 3a. It also shows the density at shrinkage limit that can be achieved through evaporative drying.

The final decision on how the stack is going to be built requires field trials and, when possible, small-scale piloting. Using the intended mechanical equipment (e.g. trucks, stackers, graders, compactors and water trucks), layers are placed iteratively in different configurations, thicknesses, number of passes of the equipment and the dumped moisture content of the material. For every iteration, sand cone tests (ASTM 2021a) or nuclear density gauge (ASTM 2021b) can be used to assess density and moisture content. During the process of compaction, the largest effect of dry density is achieved in the first few passes of the roller. After that, the compaction energy required to achieve a higher density increases exponentially, so it is seldom worthwhile applying more than five or six passes of a roller compactor in a specific material (Blight 2013). On large-scale operations, the reduction of a single pass of the roller compactor per lift could mean cost and emission optimisation in the long term. Generally, for finer material such as tailings, layers between 15 and 50 cm are commonly used.

Regardless of the final compaction specification, it is important to consider the potential variability of the material that is being placed. Commonly, dewatering plants can be affected by changes of the particle size distribution of the tailings coming from the mill, or before that by changes in the mineralogy of ore coming from the mine. Quality control and assurance (QCA) plans require compaction tests carried out periodically to account for these variabilities and to ensure that the desired compaction degree is reached. Figure 4 shows the variability on the QCA Proctor routine tests in the past couple of years in the Buriticá mine dewatered tailings stack in Colombia where the MPMDD presented variabilities of 6% with the OMC of 4%.

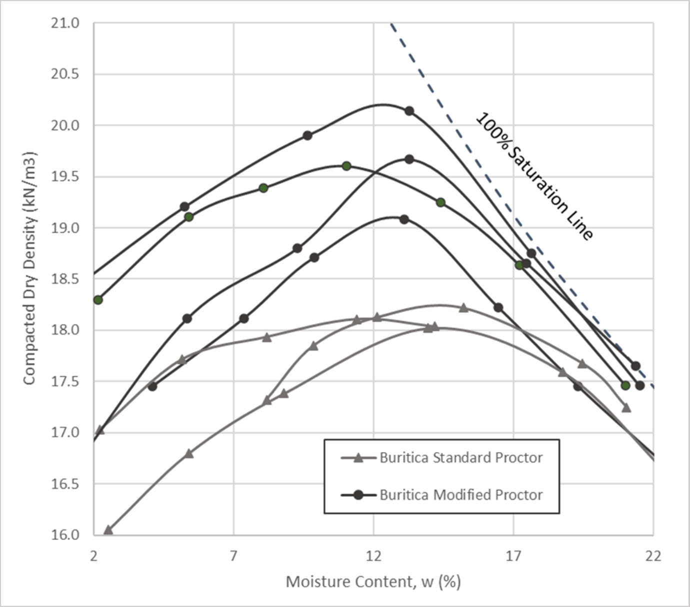


Figure 4 Set of historical modified and standard Proctor compaction test curves from Buriticá dewatered tailings stack in Colombia

Ideally, dewatered stacks are fully compacted, and all the material lies on the dilative region of Figure 2. However, the construction of a fully compacted dewatered stack is an extended, intensive and continuous earthwork operation involving several pieces of equipment burning diesel and/or consuming electricity. These costs usually go to the operation expenditures (opex), and based on SRK trade-off studies, could be higher than the opex associated with a dewatering plant (e.g. pressure filter).

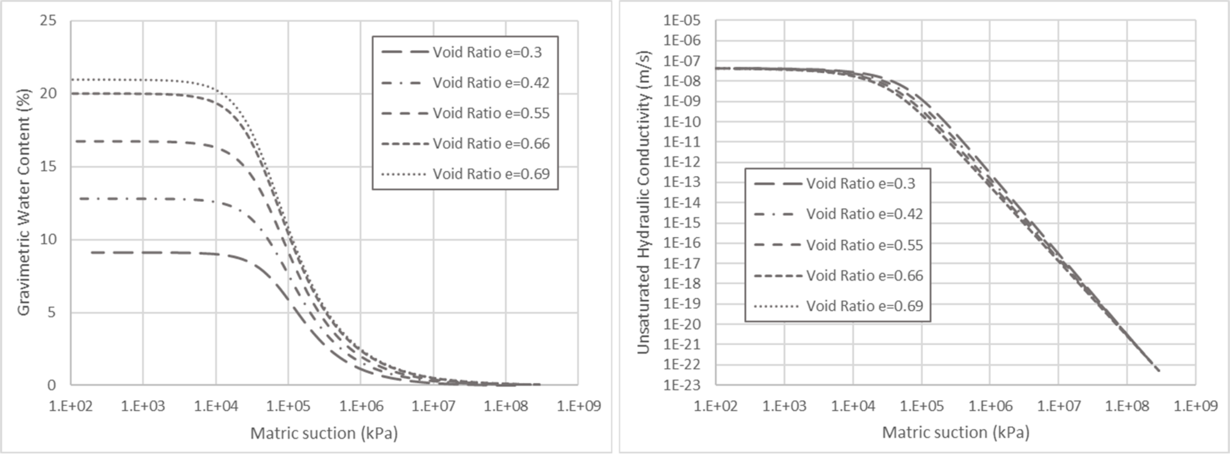
An alternative to reduce the expenditure is to split the facility into structural and non-structural zones. The structural zone is a highly compacted zone which usually contains a non-structural zone located upstream. The non-structural zone is an area of the stack where the dewatered material can be placed without compaction or with less compaction compared to the structural zone. The interaction of the structural and non-structural zones needs to be assessed, not only in terms of the stability considering the lower shear strength and higher compressibility of the non-structural material, but also on the seepage and phreatic water conditions considering higher hydraulic conductivity and higher water storage of the non-structural zone.

In some cases, depending on the characteristics of the site (e.g. topographic, climate, geological hazards exposure and seismic conditions, people at risk, consequence classification), non-structural zones might not be suitable and the entire stack may need to be compacted.

2.3 Dewatered tailings stacks as unsaturated fills

Partially saturated or unsaturated soil mechanics is relevant considering that compacted dewatered tailings stacks are unsaturated by definition. The dewatering followed by compaction at the OMC yields a placed material with a degree of saturation less than 100%. Figures 3a and 4 show the saturation lines (100%, 90% and 80% of saturation). Unsaturated materials have two mutually soluble pore fluid phases, both water and air. Bishop (1959) extended Terzaghi's (1925) effective stress theory to account for the suction provided by the fluid phases to the soil skeleton.

Soil water characteristic curves or suction-water content curves (SWCCs) show the relationship between moisture content and the suction in a particular material. Figure 5a show the SWCC for the Velardeña tailings for different densities (void ratios or porosity). The hydraulic conductivity is also affected by suction: when the air-entry value is reached, the flow of water through the granular skeleton is significantly reduced by the air in the pores, as the free water reduces and the remaining water sticks to the solid particles due to capillarity (i.e. forming water menisci and films over the particles).



(a) (b)

Figure 5 (a) Soil water characteristic curve and (b) unsaturated hydraulic conductivity function for Velardeña mine tailings

Unsaturated granular materials don't represent a problem during the operation of a dewatered tailings stack while the moisture content is kept low enough: the apparent cohesion provided by the capillary and suction at the interparticle contacts results in additional shear strength and stiffness, helping the overall stability and performance of the stack (Blight 2013). The state-of-practice during the design does not account for this apparent cohesion, which is likely the reason monitoring parameters of installed instrumentation (e.g. settlement plates, extensometers, survey monuments/prisms and radars) outperform expected values during construction and operation of the stack, even if there are deviations of the construction specifications. The practitioner must proceed with caution to avoid the 'normalisation of deviance', defined as the false sense of security after an operational procedure is changed and without immediate changes in the intended performance leading to the deviation being rationalised and assumed as safe. This normalisation of deviance is considered to be the underlying issue leading to the Space Shuttle Challenger disaster in 1986, as well as the 2014 Mount Polley and 2015 Fundão dam breach events (Vick 2017). Instead, the 'observational method' (Peck 1969) is an appropriate alternative to refine and optimise the construction of a dewatered stack but requires thorough understanding of the mechanics of the materials and the expected response under the applied changes. This usually requires good and active construction control, record keeping and instrumentation. The success of the implementation of an observational approach also relies on an owner with contractual and financial flexibility and a construction and earthwork contractor able to quickly modify procedures (Norambuena et al. 2021).

The problem with unsaturated materials arises when there is an increase in the moisture content leading to the dissipation of the suction and lubrication of the interparticle contact. Wetting can lead to settlement, collapse, or heave on the compacted surface of the stack and loss of strength leading to slope failure (Blight 2013). Operational specifications and procedures are geared to maintain the unsaturated conditions of the stack by limiting the exposure to any source of water. These considerations are not only applicable to wet climates but also dry climates prone to seasonal flash rain events that could cause ponding and infiltration.

2.3.1 Liquefaction susceptibility of unsaturated fills

The apparent gain in strength and stiffness due to suction also decreases the susceptibility of liquefaction. Since the 1980s, laboratory testing results in unsaturated soil samples show behaviours that would indicate high density materials (Yoshimi et al. 1989). However, researchers have shown that under cyclic loading, unstable liquefaction-like behaviour begins even in dense sands when the degree of saturation exceeds 60–70% saturation (Tsukamoto 2018). This observation is consistent with more recent studies (Aghazamani 2022) where excess porewater pressure buildup was evidenced on compacted samples with saturation degrees of 80% or higher. The lower density and moisture content higher than the OMC also show an increased effect on the excess porewater pressure generation (such as in Figure 6).

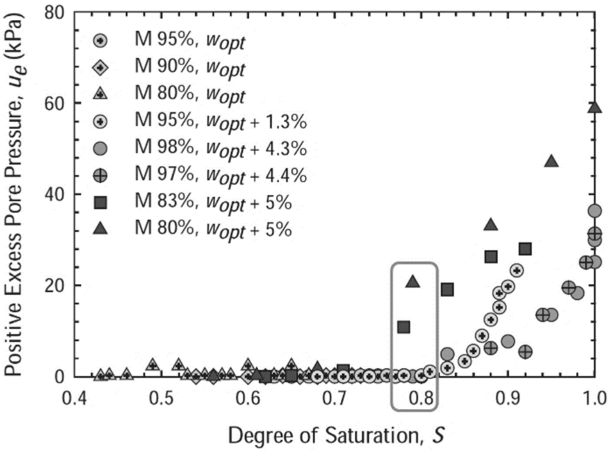


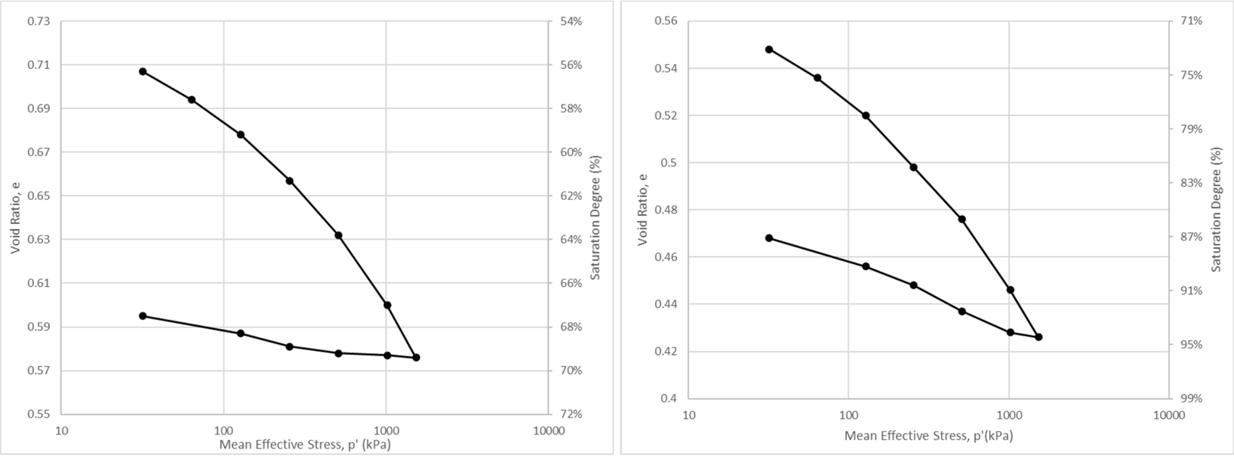
Figure 6 Evidence of porewater pressure build-up on compacted samples with saturation degree between 80% and 100% (Aghazamani 2022)

Although not strictly a geotechnical aspect, but relevant for physical stability and environmental purposes, the oxygen diffusion into the stack increases in unsaturated materials by allowing the free flow of air into the pores. Oxygen diffusion promotes oxidation and dilution of sulphides, leading to acid rock drainage and the leaching of metals, metalloids and other trace elements. With these leachates, many reactions can take place, including particle degradation, loss of mass, dissolution and precipitation of soluble salts and other secondary altered minerals. The latter could facilitate cementation and/or clogging of the pores, leading to potential reduction in the drainage capacity, which could ultimately lead to saturation (Durocher et al. 2022).

2.4 Consolidation and re-saturation

During the construction of the dewatered stack, as soon as the placement of the next layer starts, the incremental load will initiate a compression and consolidation of the underlying layer, reducing the pore space between the particles (void ratio). The magnitude of the void ratio reduction for a given load and how long it will take for the volume to stabilise depends on the material. One-dimensional or oedometer compression tests (ASTM 2011) are one option to evaluate the compressibility of the materials. This test provides a close representation of the construction of a stack in horizontal lifts. The test results can provide information on how long it will take on each load stage to stabilise after the dissipation of excess porewater pressures, which can be used to determine a safe rate-of-rise of a stack.

Figure 7 shows some oedometer consolidation test curves on the Velardeña mine tailings. The left curve was executed on a sample prepared at a density equivalent to 90% of the MPMDD while the one on the right was executed on a sample compacted to 98% of the MPMDD.



(a) (b)

Figure 7 Oedometer consolidation tests results on Velardeña mine tailings for samples compacted at (a) 90% of the MPMDD and (b) 98% of the MPMDD, showing an estimation of the saturation degree for a constant moisture content similar to the OMC

As the stack grows in height during the operation, the little water left in the pores after the compaction will start filling the shrinking pores due to consolidation. Eventually, the remnant water will cover most of the pore volume, leading to saturation. For high-rise dewatered stacks, this process is critical, not only because the deeper layers become saturated with minimal water content but also because at high stresses, the material could transition to the contractive region, with potential of liquefaction and strain softening.

Little or no variation of moisture content is quite representative of arid climates. In the Velardeña pilot stack, the moisture content profile in depth seems to get locked in around the same moisture content used during compaction. This agrees with the model presented in Lupo & Hall (2010) which shows that the draining and reduction of moisture content on low permeability stacks could take several years. In Figure 7, parallel to the void ratio axis is the saturation degree which represents how the saturation degree increases as the material compresses if the moisture content stays close to the OMC (~12%).

Interestingly, the higher density reaches the critical saturation degrees zone (>80%) with 400 kPa of vertical effective stress, while the lower density is far from the zone even at the higher 2,400 kPa of vertical effective stress. This seems contradictory, but looser samples mean larger voids to be filled with the same water content.

In wet climates, precipitation and runoff can seep and drain down, recharging deeper layers faster with higher permeability. In this scenario, the saturation of deeper layers is almost certain, and the best way to control this is to ensure there is capacity to drain water from the system so the phreatic level doesn’t rise to critical levels. Instrumentation and monitoring should be implemented to evaluate the seasonal variation of the phreatic levels and saturated zones within the stack.

3 How high is too high?

Answering the question 'How high is too high?' will require a conceptual framework at an early stage that allows the practitioner to avoid the susceptibility of static or cyclic liquefaction of a dewatered tailings stack by limiting the target height. The previous section provided a general understanding in key geotechnical elements to understand the implications of the contractive behaviour, the saturation-like behaviour in unsaturated materials in terms of potential porewater pressure buildup, and examples on how unsaturated materials can become saturated due to self-weight consolidation.

The early-stage assessment requires determining the CSL by completing a series of compressions drained and undrained triaxial tests with measurement of the void ratio at the end of the tests (Been & Jefferies 2016). Proctor compaction tests and oedometer consolidation tests prepared at initial densities defined by the compaction tests (e.g. 98%, 95% and 90% of the MPMDD or SPMDD) will also be required. Some of these tests were executed for the Velardeña tailings, and the results were presented in Section 2.

The results of the CSL and the oedometer compression curves will be integrated in a plot and will look similar to Figure 8. Rola (2020) provides a comprehensive approach on how to combine oedometer consolidation curves, usually plotted void ratio (e) against vertical effective stress (σ'v), into the void ratio (e) against the mean effective stress (p').

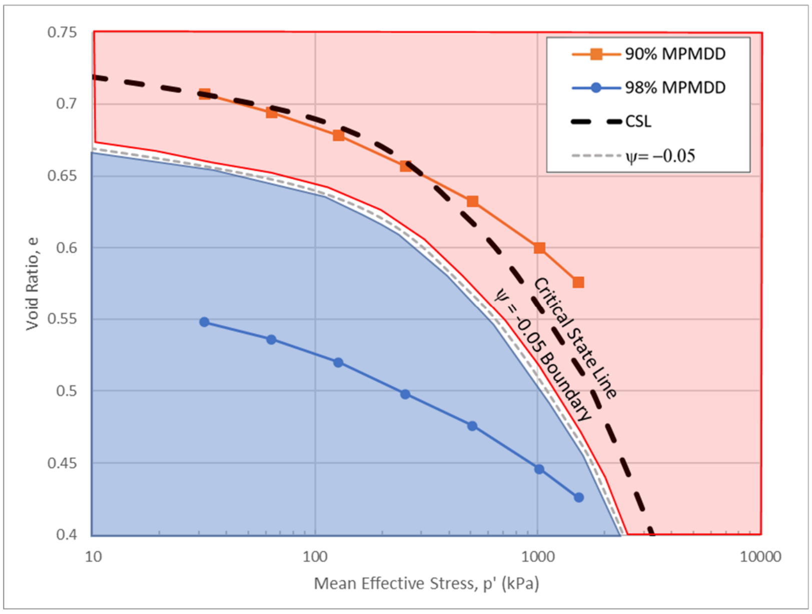


Figure 8 Overlap of the critical state line and the consolidation trajectories for different initial densities

From Figure 8, it is possible to observe the loose sample (90% MPMDD) is in the contractive region from the initial load stage, crossing the CSL at 300 kPa of mean effective stress. The denser sample (98% MPMDD) doesn't reach the contractive behaviour boundary even at the highest effective stress tested.

Sometimes the CSL is represented as a straight line, but lab testing data on various materials, including tailings (Verdugo 1991; Smith et al. 2019; Macedo & Vergaray 2021; Reid et al. 2021) show that the CSL curves with a steeper slope as it reaches higher confining stresses, and that a power-law curve provides a better representation of a CSL. The lower lifts of large-scale dewatered tailings facilities of 50 to 80 m could easily get beyond the 1 MPa of mean effective stress where the curve get highly non-linear (Ghafghazi et al. 2014).

Reliable laboratory testing in high stress ranges need to be performed when evaluating high-rise facilities. Extrapolating the CSL at higher stress levels should not be done considering the curvature at high stresses can lead to non-conservative interpretations. However, the lab equipment required to execute testing at high stresses is not necessarily available at the local labs. In the case study, the maximum available effective stress used in the triaxial test executed to characterise Velardeña tailings' CSL was 800 kPa, equivalent to 60 m. Practitioners shouldn't recommend stacks with elevations that mobilise stress levels that haven't been represented and understood in the lab.

As Davies et al. (2002) noted after reviewing several dam failure cases, it is better to run reliable and representative lab tests on an early stage than to experiment during the construction and operation of the stack and find something unexpected "…in the giant stress-controlled test represented by the dam itself, contractant undrained behaviour clearly resulted" after the lab tests showed the tailings were dilatant.

Considering the framework is relatively easy to set up, it could also be used to optimise and run sensitivities. For instance, it was possible to test 95% of the MPMDD compaction after testing 98% of the MPMDD of the Velardeña tailings showed a very dilative response. Similarly, an oedometer consolidation test should be carried out to the objective density to provide the representative compression curve of the material and the result can be overlapped with the CSL curve. Figure 9 shows the potential compression trajectory of Velardeña tailings under 95% of the MPMDD and the 800 kPa of mean effective stress (~60 m) which lies within the dilative region, and the degree of saturation is 79% for the OMC at the same stress level.

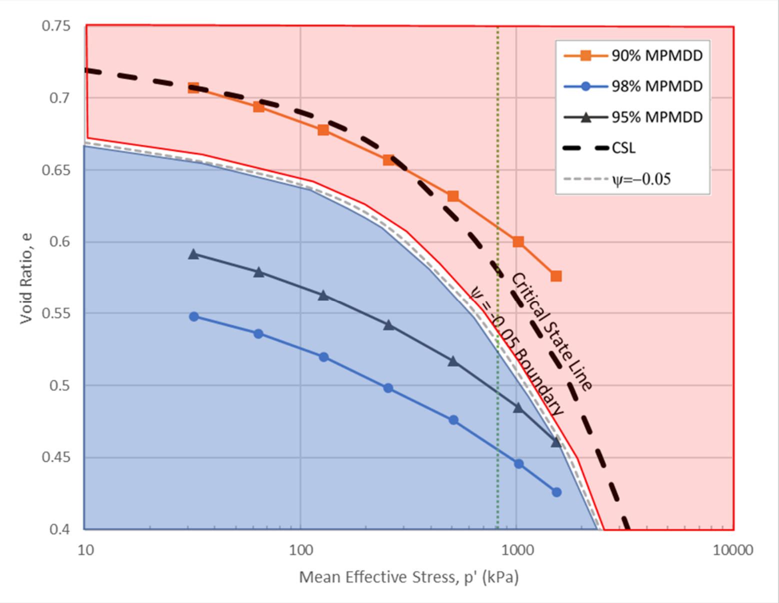
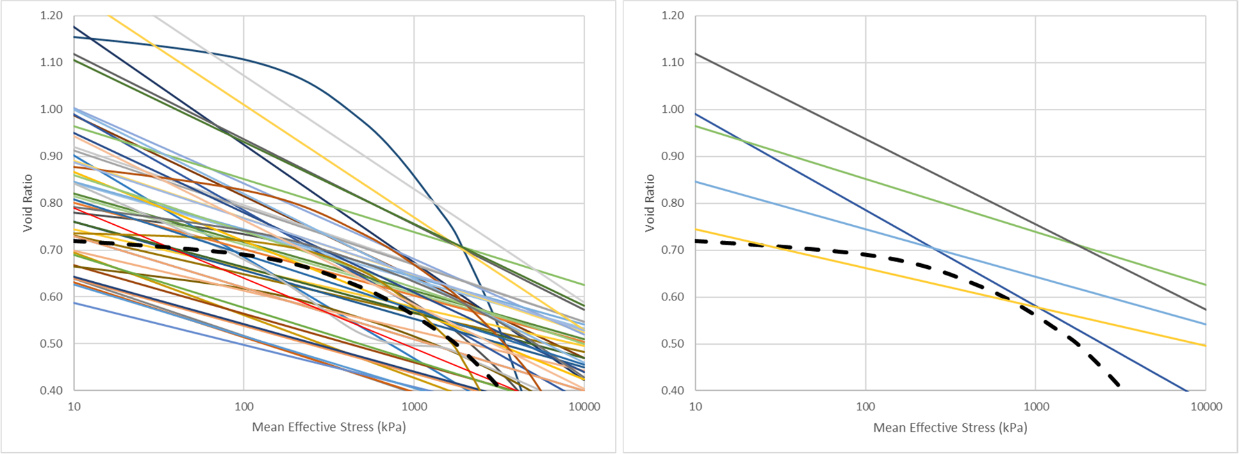


Figure 9 **Overlap of the critical state line and the consolidation trajectories including an expected compression curve representative of the optimised case with 95% MPMDD**

To add robustness to the evaluation, particularly on the definition of the CSL, test data available in the technical literature can be compared for benchmark and sensitivity. Filtering by fines content, type of tailings, plasticity, specific gravity or other relevant parameter or property allows for better suited data for comparison in the particular case. Figure 10a shows the databases of Smith et al. (2019), Macedo & Vergaray (2021), and Reid et al. (2021), plus additional SRK data, and highlighted is the CSL of the Velardeña tailings. In Figure 10b, the filtered data from lead–zinc tailings case studies, same as Velardeña, are isolated and plotted together.



(a) (b)

Figure 10 (a) Literature CSL Compilation to be used for an early-stage assessment (Smith et al. 2019; Macedo & Vergaray 2021; Reid et al. 2021) including Velardeña CSL (black dashed line); (b) Lead-zinc tailings CSLs isolated

4 Case study of dewatered tailings stacks operation

4.1 Velardeña pilot

The Velardeña mining district is in the municipality of Cuencamé, in the eastern area of the state of Durango, Mexico, approximately 120 km from the city of Torreón, Coahuila. The mining activity in the Velardeña district dates to 1606. Since 2003, the Velardeña mine has been fully owned and operated by Industrias Peñoles.

Velardeña is a polymetallic underground mine that processes minerals at a nominal rate of 8,200 tpd and produces concentrates of zinc, lead and copper by flotation of crushed and milled sulphide minerals. Based on the current mine plan, Velardeña has enough resources and reserves to operate until 2048.

In general, the Velardeña mine has tailings with the following geotechnical parameters and properties:

- Specific gravity = 3.29.
- Fines content (#200 – 0.072 mm) = 95−98%.
- Atterberg limits: IP = 4 / LL = 22/ PL = 18.
- Unified Soil Classification System (Wagner 1957): CL – ML.
- Compaction maximum dry density modified Proctor: 21.42 kN/m^3 (e = 0.515) and OMC: 11.8%.
- Compaction maximum dry density standard Proctor: 19.23 kN/m^3 (e = 0.678) and OMC: 12.5%.
- Saturated hydraulic conductivity: 2x10^{-8} m/s.
- Concentration of solids (weight) of the slurry: 65%.

There are three TSFs at Velardeña. TSF1 is in passive care and is associated to the historical mining activities before Peñoles' involvement. TSF2 and TSF3 (split in Cell 1 and Cell 2) are slurry-based upstream construction facilities in active use. The management of tailings in these facilities is expected to continue until 2026, when the new TSF4 is commissioned.

On the basis of a multiple accounts analysis (MAA) (Robertson & Shaw 1998) and a decision workshop, it was suggested that the new TSF4 be a dewatered tailings stack. Both the MAA and the workshop considered aspects such as best available technologies, best available practices, dam safety, potential consequences, people at risk, land use and availability, life of mine, life of the proposed facility, weather, operational experience, and geotechnical understanding of the tailings.

The hydraulically deposited slurry tailings in the active TSFs will be the source of dewatered tailings for the new dry stack facility after they dry out. Depending on the season, it is possible to harvest the tailings 70 to 90 days from the end of deposition. After this time, the first few metres of the tailings reach a moisture content of 18−20%, low enough to be excavated and hauled. The areas where the cycle of deposition, drying and excavation occurs are called 'drying pools' and are currently being considered as the engineering design of the TSF4. In parallel, trade-off studies are being done on filtration technologies and a feasibility study is underway for the engineering of a filtration plant.

To prove the concept of the large-scale operation, a pilot dewatered stack was proposed and designed. The design considered the placement and compaction of 215,000 m^3 of dewatered tailings against a hillslope with side slopes of 2.3:1.0 (H:V) with a maximum thickness of 12 m built on 30 cm lifts compacted to 98% of the SPMDD at the OMC ±2%. The stability analyses were based on Canadian Dam Association provisions for mining dams (CDA 2019). The construction started in June 2021 and was completed in December 2022 and proved construction rates up to 5,200 m^3 per day of compacted tailings (or 10,140 tpd). Figures 11 and 12 show the different stages of the excavation, haul, dump, spreading and compaction of the Velardeña dewatered tailings on the pilot stack.

(a) (b)

Figure 11 **(a) Excavation activities on the Cell 2 of TSF3 to source dewatered tailings to TSF3; (b) Dumped tailings with 18−20% moisture content**

(a) (b)

Figure 12 **(a) Spreading of the dumped tailings using dozers and graders; (b) Compaction with smooth vibrator rollers to the 98% of the SPMDD**

The quality control (QC) of the stack considered the use of the sand cone method (ASTM 2021a) and the nuclear gauge (ASTM 2021b) to measure the compaction degree and moisture content. The nuclear gauge was used on every 500 m^3 of hauled material or every 50 m of the compacted lift in a triangular pattern. The sand cone test was used as quality assurance of the nuclear gauge, executing at least two measurements per layer adjacent to the nuclear gauge or at least one every 3,000 m^3 of hauled material. Figure 13 shows a completed lift of the pilot stack executing both the sand cone and the nuclear gauge tests. The technician needs a few blows of a sledgehammer to excavate the tailings to execute the sand cone.

Figure 13 Quality control of the pilot stack including sand cone and a nuclear gauge

Figure 14 show the compaction records of the pilot stack as part of the QC tests. The gap in data corresponds to time spent on the third raise of TSF3. At the OMC, the tailings require three passes of a 10 t smooth drum vibro-compactor to reach the 98% of the SPMDD.

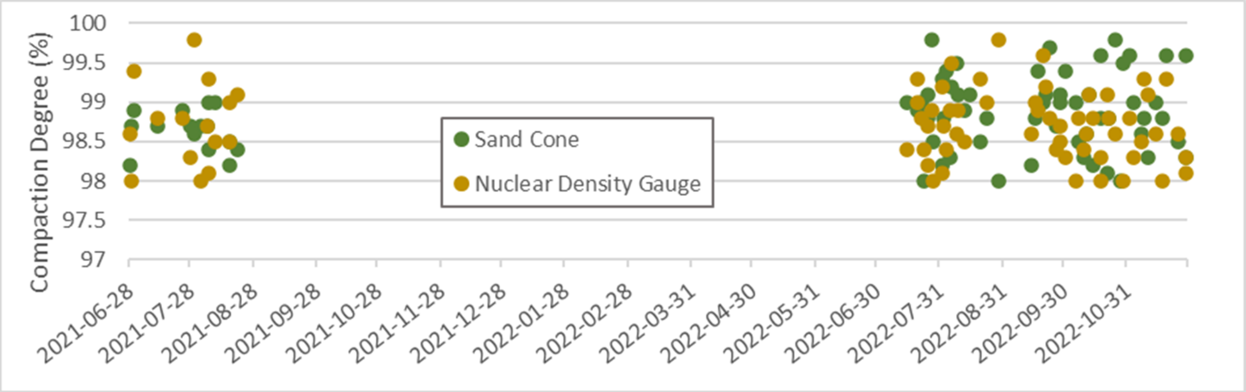
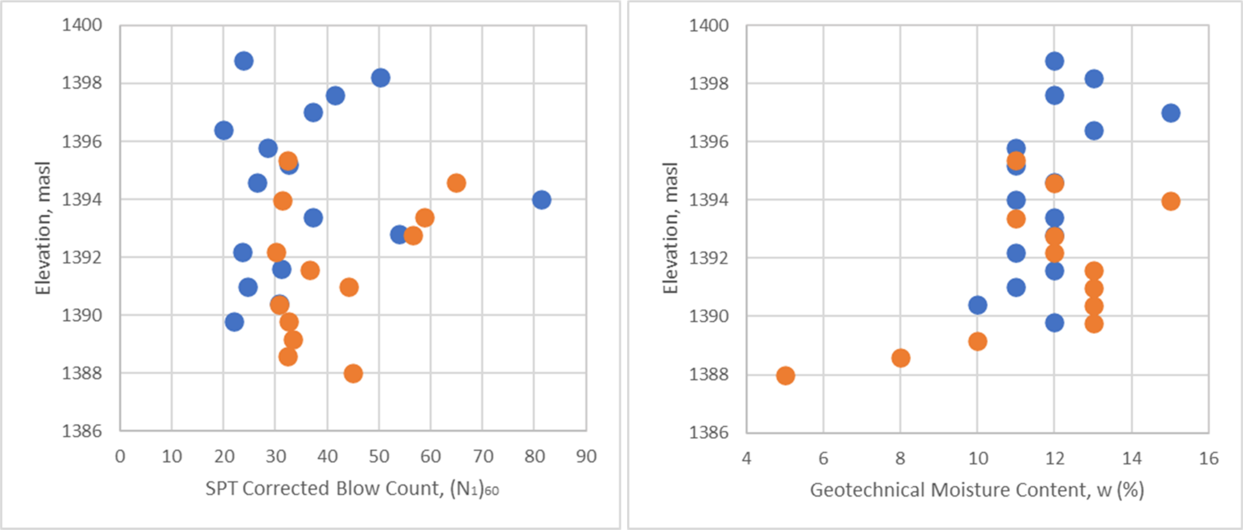


Figure 14 QC records during the construction of the pilot dry stack

At the end of 2022, a site-wide investigation was executed to evaluate the conditions of the active TSFs and included cone penetration tests (CPTu) including porewater dissipation tests, shear wave velocity and compressional wave velocity measurements at every metre of penetration. The site investigation also included a drilling rig to do the pre-drill for the CPTu soundings, with an automatic hammer to execute standard penetration tests (SPTs) where the CPTu maxed out (25 MPa of tip resistance q_c). The SPT was carried out continuously until the blow count of the SPT reached refusal (N_{spt} >50), usually at natural ground, or was low enough (N_{spt}<10) to start penetrating with the CPTu again.

The pilot stack was evaluated during the 2022 site investigation, and two CPTus were attempted but both maxed out early in the penetration, measuring 25.93 MPa of tip resistance (q_c) at 18 cm of penetration. Because of the failed attempts to execute CPTu soundings on the pilot stack, continuous SPTs were executed. Figure 15a shows the corrected blow count of the SPTs and Figure 15b shows the moisture content measurement of samples recovered from the SPT split spoon.



(a) (b)

Figure 15 (a) SPT corrected blow count records and (b) moisture content profile for two boreholes executed on the pilot stack

The low moisture shown in the lower elevation in Figure 15b is attributed to the exposure of the first few layers from 7 October 2021 to 28 June 2022, at which time construction efforts were shifted to the third raise of TSF3, and also to the natural terrain which could have absorbed some of the moisture content. The SPT results show scattered data, with corrected SPT blow counts ranging from 20 to 80. There is no clear correlation of this variability with moisture content measurements or compaction degrees.

5 Conclusion

This paper provides an initial reference and practical recommendations on some geotechnical elements for the design and operation of dewatered tailing stacks. These could help flag and mitigate potential risks that practitioners might encounter with large-scale dry stack operations, which have proven to be a reliable and robust approach to manage tailings but have not yet been proven for very high throughputs operations (>50,000–100,000 tpd) targeting high-rise facilities.

Using CSSM together with other geotechnical concepts, a conceptual framework was proposed to link the expected mechanical behaviour and engineering performance of the stack with the expected loading conditions, based on the compressibility and consolidation properties of the material.

The attempt to answer the question ‘How high is too high?’ is provided with a practical exercise describing how a ‘dry’ and compacted layer can become saturated and contractive on terms of CSSM, with the potential of porewater pressure buildup, even in zones under partial saturations zones (>80%).

The conceptual framework proposed herein should be considered as an initial/early assessment and should never replace a robust modelling of the physical components involved in the mechanics behind the loading of a dewatered stack.

An unsaturated consolidation model of the stack, tracking the construction process using SWCCs representative of the materials, accounting for the evolution of the pore space and incorporation of environmental inputs (e.g. precipitation and evaporation) is highly encouraged. This will account for the transient conditions in stability assessments.

Numerical deformation stability models are recommended to evaluate design aspects such as seismic performance and operational controls such the rate-of-rise. Both lab testing and constitutive models should be completed to identify and represent brittle behaviour (strain softening) materials, in line with the requirements from the GISTM (Global Tailings Review 2020) and the recent provisions from Bulletin No. 194 by ICOLD (2022).

An additional step to include in the numerical deformation stability models is to evaluate the vulnerability of the stack as per Ledesma et al. (2022). This is a way to assess the robustness of the structure if a number of unforeseen events occurred.

Alternatives to filtration such as evaporative drying of tailings is an economically viable way to source dewatered tailings in dry climates. However, a significant amount of water is lost to the atmosphere that could be reused in the mine as a more sustainable use of water, and one of the most relevant factors on the ESG framework and organisations is pushing for more responsible stewardship of water (ICMM 2014, 2017, 2021).

With the new generation of large-scale dewatered stack starting to be built, it is critical to avoid overconfidence. The design and the operation should ensure low moisture and dense conditions, particularly the structural zones. Deviations of these requirements needs to be understood and accounted for.

> *"'Critical' really meant what it said – it was the criterion of a safe density in constructed engineering work, with the practical concern to avoid sudden transitioning of drained construction with no excess pore pressure, into an undrained liquefaction failure." Been (2016)*

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