Filtered tailings can be a viable option for managing tailings disposal at mines. Some of the advantages of filtered tailings include: i) reduction in water consumption, as more process water can be recycled; ii) the filtered tailings can often be stacked (often referred as dry stack tailings) to reduce the footprint for tailings storage; and iii) the dry stack tailings can often be reclaimed concurrent with placement, thereby reducing reclamation costs. Filtered tailings have these advantages over slurry, thickened, and paste tailings as the filtration process used (either vacuum belt or mechanical presses) essentially advances the consolidation process (which can take tens of years or more to achieve with traditional slurry disposal) to form an unsaturated cake. The filter cake often has a consistency of moist sand or silty sand, with geotechnical and hydraulic properties amenable to stacking and compaction. While thickened and paste tailings may be able to achieve beach slopes in the 3 to 6 percent range, dry stack tailings may be stacked with stable slopes in the 20 to plus-30 percent range, with compaction.

This paper presents the primary geotechnical considerations for the design of dry stack facilities. The designs issues discussed in this paper include rate of stacking, stacking height, seepage/infiltration, and settlement. In addition, this paper addresses some common misconceptions regarding the geotechnical and hydraulic performance of dry stack tailings based on actual lab and field data.

1 INTRODUCTION

Filtered tailings can be viable alternative to slurry, thickened, or paste tailings disposal at many mine sites. Some of the key advantages of filtered tailings disposal over the other methods includes: i) minimized water consumption (most of the water is recovered during the filtration process); ii) as discussed later in this paper, filtered tailings often have properties that are amenable to stacking, thereby reducing the land requirements for disposal; and iii) the filtered tailings stack provide a stable land form, allowing reclamation to be conducted concurrent with disposal, which can save both time and cost for the operation.

Tailings filtration can be accomplished through either vacuum or mechanical press. The filtration process basically accelerates the consolidation process that would naturally occur in other tailings deposits (slurry, thickened, or paste). The resulting filtered product is an unsaturated (often between 50 to 75 percent saturated) material that is firm with a low compressibility and low hydraulic conductivity. In this state, the filtered tailings are often termed “dry stacked” tailings, since the materials resemble a moist sand that can be stacked and compacted into a stable landform.

In the design of dry stack tailings facilities, it is important to consider the materials characteristics that are unique to dry stack tailings as well as operational and material handling considerations. These issues are discussed in the following sections.
2 DRY STACK TAILINGS CHARACTERISTICS

Before discussing dry stack tailings design issues, it is often useful to review some typical characteristics of filtered tailings.

2.1 Particle Size

Particle size is not a unique characteristic of filtered tailings. However, it is worth a brief discussion in terms of what particle size gradations have been successfully used at some dry stack operations. Figure 1 presents a plot of particle size gradations from several dry stack tailings projects. The data shown on this graph shows that successful filtered tailings projects have been completed on materials with very high fines content.

![Figure 1. Tailing particle size gradations.](image)

The particle size data presented in Figure 1 illustrates that dry stack tailings projects are not limited to low fine content tailings. Advances in filtration processes and equipment have made it possible to filter relatively fine materials with good results.

2.2 Shear Strength

The shear strength of dry stack tailings will vary, depending on the moisture content and density of the tailings, and drainage conditions within the stack. From a design standpoint, it is important to recognize that the density, moisture content, and drainage conditions within the stack are changing as more tailings are placed in the dry stack. In addition, the tailings density and moisture content may vary depending on filter efficiency and ore mineralogy. For the most part, dry stack tailings tend to exit the filtration unit near the maximum dry density (based on the Standard Proctor density) and slightly wet of optimum. At these conditions, the tailings can have a high degree of shear strength, and are suitable for placement and compaction. Figure 2 presents a plot of shear strength (plotted in effective stress path space) from five different dry stack tailings subjected to Consolidated-Undrained (CU) triaxial compression tests.
All of the samples tested in Figure 2 were remolded near the density and moisture content of the tailings from the filtration units, and then saturated prior to testing. The purpose of the data shown in Figure 2 is to illustrate the relatively high shear strength that can be achieved with fine-grained, filtered tailings (without cement or lime amendment). The ultimate failure surface shown in Figure 2 could be described with an effective friction angle of 35 degrees, in terms of a traditional Mohr-Coulomb shear strength criteria.

In addition to the high shear strength, it is evident from the stress path that the filtered tailings exhibit dilatant behavior under undrained compression (for the five tailings samples shown in Figure 2). This behavior reflects the relative dense condition of the tailings from the filtration units. The observed dilatant behavior in Figure 2 needs to be considered when assessing slope stability, deformations under seismic loading, and liquefaction assessments for dry stack facilities.

For the design of dry stack tailings facilities, it is recommended that the filtered tailings be tested over a range of dry densities and moisture contents, to reflect the variability of materials that could be delivered to the dry stack. Filtration equipment (presses and belts) can generally provide materials with consistent dry densities and moisture contents, but some variability may occur due to changes in ore mineralogy, loss of filter efficiency by plugging, or increase in throughput above the design level.

Dry stack operations may also experience brief periods when overly wet tailings may need to be placed onto the dry stack facility (e.g. upset conditions). Depending on how these materials are delivered (low density, high moisture content, rapid placement rate, etc), filtered tailings with contractive behavior may be placed within the dry stack. Under shear, contractive tailings could lead to very low undrained shear strengths within the dry stack. The placement of these materials within the dry stack is an important design consideration, which will be discussed in the Section 3.

2.3 Hydraulic Conductivity

The hydraulic conductivity (saturated) of filtered tailings tend to be relatively low, typically less than $1 \times 10^{-6}$ centimeters per second (cm/sec). The hydraulic conductivity will be dependent on the amount of fines, mineralogy of the ore, and density of the material. Figure 3 presents a plot of saturated hydraulic conductivity measured from several samples of filtered tailings. The samples shown in Figure 3, were remolded to the dry density and moisture content of filtered tailings. The fines content (finer than 0.075 mm) of the materials tested ranged from 60 to 90 percent.
As shown, the measured hydraulic conductivities ranged from 6.7x10^{-6} to 1.7x10^{-8} cm/sec, indicating the tailings placed in the dry stack have low to very low hydraulic conductivities. The low saturated hydraulic conductivity, combined with being placed as an unsaturated material, minimizes that quantity of water (e.g. precipitation) that can infiltrate through the dry stack. Section 3 provides additional discussion on the infiltration potential through dry stack tailings facilities.

2.4 Compressibility

The compressibility of filtered tailings is an important consideration for dry stack design, as it directly affects the stacking rate and configuration. As presented earlier, the filtered tailings are typically delivered in an unsaturated state (usually between 50 and 75 percent saturation). However, the degree of saturation of the tailings is a function of porosity, which changes as the depth of the dry stack increases (i.e. lower porosity at the bottom of the stack, and higher porosity at the top of the stack). A plot of porosity versus dry stack depth is presented in Figure 4, showing the reduction in porosity due to the compression of the tailings.

Figure 3. Filtered tailings saturated hydraulic conductivity.

Figure 4. Typical tailing porosity with increasing dry stack depth.
If the filtered tailings are highly compressible, there is a potential for the porosity to decrease to a point where the dry stack tailings become fully saturated. Once a portion of the dry stack becomes fully saturated, then any additional loading (e.g. adding another lift of tailings), could give rise to excess pore water pressures. The presence of either saturation and/or excess pore water pressures within the dry stack, could give rise to stability issues, therefore it is important to quantify the compressibility of the tailings.

Figure 5 presents a plot of filtered tailings compressibility from several dry stack projects. The tailings compressibility has been converted from that shown in Figure 4, to saturation versus depth of tailings. The format shown in Figure 5 can be readily integrated into dry stack facility design. As shown, the compressibility of the filtered tailings can vary from high compressibility (Tailings B and B2) to low compressibility (Tailings A).

The curves presented in the compressibility plot show that for design, saturated conditions within the dry stack would be anticipated to develop within 25 m of stack height for Tailings B; within 50 m for Tailings B2 and D; and saturated conditions are unlikely to develop in Tailings A, A2, and C. It must be noted that the development of saturation within a dry stack is not a fatal flaw, rather it needs to be addressed in the design so that stability of the facility is not negatively impacted.

3 DRY STACK TAILINGS DESIGN CONSIDERATIONS

The discussions presented in Section 2 provided some general observations regarding the characteristics of filtered tailings shear strength, permeability, and compressibility. This section discusses integration of these characteristics into design.

3.1 General Design Approach

The design of a dry stack tailings facility is a balance between materials handling and construction with the geotechnical properties of the tailings. From a materials handling standpoint, the facility needs to be designed to support the method of transport and deposition of the tailings to the facility (either conveyor or truck haulage). Therefore, the overall layout needs to include any access roads or conveyor corridors. The site topography and distance from the filter plant may dictate the method of delivery, however the tailings properties (moisture content) may also in-
fluence this decision. During the operation of the dry stack, provisions must be made to handle overly wet tailings, should upset conditions occur in the filter plant. Therefore, the design of the materials handling systems and equipment should be robust to handle a wide range of materials (unsaturated to saturated tailings).

Placement and compaction of the tailings will also need to consider a wide range of materials during operation. In general, it is good practice to place and compact unsaturated tailings along the downstream end of the facility, forming a structural zone to support the dry stack facility. Behind the structural zone, the tailings can be placed with no or low compaction. These tailings may also include overly wet materials that may have low shear strength or high compressibility.

The size and extent of the structural zone can developed based on stability analyses to support and contain the materials behind the structural zone. The design basis for the structural zone needs to consider material strengths, static and seismic loading, and potential water management concerns. A generalized cross-section through a dry stack facility is shown in Figure 6.

In some cases, a rockfill buttress or rock mulch may be added along the outside slopes of the dry stack facility to enhance stability, provide benching for slope reclamation, and for erosion protection of the out slopes.

3.2 Stacking Height

The design of the dry stack height is generally based on slope stability analyses conducted on several sections through the dry stack facility. The stability analyses need to consider:

- Shear strength of all the materials within the section (tailings, foundation, rockfill buttress, etc). The tailings shear strengths need to be derived based on drained or undrained laboratory testing. The drainage conditions (drained/undrained) assumed in the stability analyses should reflect those that could develop through operation. Data, such as that presented in Figure 5 can be used to establish if zone(s) of saturation may develop within the dry stack. If saturation may be present, then the designer will need to conduct some additional engineering analyses to estimate the magnitude of excess pore pressures that may be present (if any).

- Presence of a static groundwater surface. As indicated previously, the presence of groundwater is not fatal flaw (unless the tailings must remain dry for geochemical reasons) in a dry stack design. The design must be developed to provide a stable landform in the presence of the groundwater surface.

- Seismic loading and residual shear strengths. Seismic loading must be considered for slope stability for operational and post-closure configurations. Depending on the location and material properties of the tailings, seismically-induced permanent deformation should also assessed. These assessments need to consider the dilatant behavior of filter tailings (if it is present) as shown in Figure 2. Material dilatancy may have a significant effect on post-earthquake material strengths and development of permanent deformations.

![Figure 6. Generalized dry stack cross-section.](image)
3.3 Stacking Rate

Stacking rate needs to be considered in cases where the tailings exhibit a high degree of compressibility (see Section 2.4). Highly compressible tailings, if stacked too quickly, may generate excess pore pressures, which could compromise stability of the dry stack. If high compressible tailings are to be included in the dry stack design, the following approaches may be considered:

- Include multiple deposition points, so that tailings can be distributed across the facility, effectively reducing the stacking rate. This is often the most cost-effective and practical approach to control compressible materials.
- Design a substantial structural fill zone to support low shear strength tailings mass. While this can easily be designed, the cost of construction and scheduling needs to be considered as part of the feasibility of this approach.

3.4 Infiltration and Surface Water Management

One of the most common misconceptions with dry stack tailings is that surface water (e.g. precipitation or run-on) will readily infiltrate through the tailings, and could saturate the stack leading to failure or sloughing. Experience from actual operating dry stack operations have shown that infiltration through the dry stack is not a significant issue, as long as proper surface water management controls are employed. As shown in Figure 3, the saturated hydraulic conductivity of filtered tailings is typically quite low. This, in combination with the fact that the tailings are placed in an unsaturated state, results in very low infiltration through the dry stack. Even if water is ponded at the surface, the infiltration rate will be limited by the low saturated hydraulic conductivity.

Figure 7. Example of infiltration through dry stack tailings.
The rate at which the infiltration front moves through the tailings can be assessed using one or two-dimensional seepage models. An example showing the infiltration front moving through a one-dimensional section of dry stack tailings is shown in Figure 7. In this example, water is ponded on the surface of the dry stack. The saturated hydraulic conductivity of the tailings is $5 \times 10^{-7}$ cm/sec. As shown in the figure, the infiltration front requires a very long time to move through the dry stack column, and does not readily infiltrate.

For most dry stack tailings facilities, the majority of the precipitation runs off the surface (due to the low hydraulic conductivity of the tailings) and can be collected by surface water management channels. It is prudent to design the dry stack facility with the upper surface graded to drain water away from critical stability areas (e.g. downstream buttresses or structural zones) during the wet season. Integrating surface water collection channels into the dry stack design can minimize the potential for infiltration through the stack and provide a way manage surface water from the facility.

4 CONCLUSIONS

Dry stack tailings facilities can be a viable option for tailings management at mining operations by minimizing water consumption, minimizing the footprint for tailings storage (by stacking), and allowing concurrent reclamation of the dry stack, thereby reducing costs. The design of the dry stack facilities needs to consider the geotechnical properties of filtered tailings. This paper presents actual test data from several filtered tailings projects and discusses the characteristics of the materials in terms of design. Key characteristics include relatively high shear strength at the dry density and moisture content of the filtered tailings, low hydraulic conductivity, and compressibility.

Design considerations for dry stack tailings facilities are provided based on performance from actual facilities. The design considerations can be used to integrate materials handling and construction issues with the geotechnical characteristics of the filtered tailings.