IMPROVEMENT IN THE STABILIY OF UPSTREAM METHOD PHOSPHATE TAILINGS DAMS WITH ROCK FILL SHELLS

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Abstract

Upstream method tailings dam construction has been used throughout the world as an economic method for containment of slurry deposited tailings waste as hydraulic fill. These types of dams can be engineered to be stable in low seismicity zones of the world with control of the water pool away from the dam limits. Upstream method dam raises typically include a starter dam for development of a peripheral tailings beach sloping toward an interior water pool. A return water system from the impoundment water pool to the plant may include gravity decant towers and pipes draining beneath the impoundment or a floating barge pump system on the water pool surface. Incremental upstream method dam raises above the starter dam may include three general types of raises including: 1) perimeter dike fills constructed on the settled tailings beach using the nearby tailings beach materials or impoundment borrow, 2) rotating paddock cells with walls for separation and drying of settled tailings, or 3) hydro-cyclone towers along the dam crest for separating tailings sand piles from the slurry. The overall slope stability for the upstream method dam raises depends on the strength and drainage characteristics of the perimeter hydraulic tailings fills and the underlying foundation materials.

Waste materials generated in the phosphate industry include phosphatic clay tailings from the mine beneficiation plants and gypsum tailings as a waste by-product from the fertilizer process plants. Both upstream method and downstream method tailings dams have been constructed for phosphatic clay containment with upstream method dams generally constructed for gypsum waste containment. This technical paper will analyze the placement of a relatively thin rock fill shell on the exterior slopes of an idealized upstream method tailings dam section. The analyses indicate that the placement of a relatively high strength rock fill shell cover on the exterior slope significantly improves the overall dam stability.

Keywords: Tailing Dams, Upstream Method Raises, Rock Fills, Dam Stability

Introduction

Upstream method tailings dams have been used extensively in the mining industry in the 20th century with less frequent use in the 21st century. This type of tailings dam typically consists of hydraulic pipe spigot, paddock cell or hydro-cyclone peripheral deposition of tailings beach material to develop an exterior embankment fill with a sloping hydraulic tailings fill surface to an interior water pool.

The hydro-cyclone sand dam construction has been more common for copper tailings dams, due to the higher mill grind sand content available in the copper tailings compared to other types of finer grind mill tailings.

The upstream method tailings dams are the most economic to construct for dam raises, unless large quantities of excavated mine overburden waste rock materials are locally available for centerline or downstream method dam construction. The upstream method dam construction was common into the 1980's and 1990's, however studies of world wide dam failures indicate hydraulic fills are more susceptible to instability from seismic (earthquake) liquefaction, overtopping, and tailings delivery or water return decant pipe breaks compared to downstream method compacted earth and rock fill tailings dams [5]. A fast rate of rise in hydraulic fill tailings disposal operations can also increase the potential risk of static liquefaction [4]. Therefore upstream method tailings dams have seen less frequent use in recent times in high seismicity zones of the world, as well as any areas where the tailings dam can be classified as a high hazard structure.

Compacted rock fill shells have been used to improve the stability of upstream method hydraulic fill tailings dams in high seismic zones since the 1970's, starting with the Codelco copper tailings dams in central Chile. This paper will present a general overview of upstream method dam construction, and then focus on the improved stability of an idealized tailings beach dam section strengthened by an exterior rock fill shell. Rock fill shell construction can be applied to any of the various types of upstream method dam raises to contain and enhance the stability of the lower strength hydraulic tailings fills, provided the underlying foundation subgrade can remain drained and stable.

Upstream Method Dam Construction

1. General

The upstream method dam construction requires an earth or earth and rock fill starter dam of sufficient height in the valley bottom to develop the required perimeter tailings beach width for stable dam raises above the starter dam crest. The upstream method dam relies on the strength and drainage of the perimeter slurry deposited and settled tailings beach material for raised dike construction. Where practical, the more coarse tailings beach materials are deposited around the perimeter of the impoundment to provide better strength, drainage and containment for the finer low strength tailings slimes materials deposited on relatively flat grades further in the interior toward the water pool.

There are generally three types of tailings slurry disposal techniques for developing a perimeter hydraulic fill for upstream method dam raises including: 1) multiple point pipe spigot deposition with dike fill raises above the settled and dried tailings beach surface, 2) paddock cell and dike wall construction above settled and dried tailings cell rotations, and 3) hydro-cycloned sand pile deposition from elevated towers forming the dam crest. The pipe spigot and paddock cell raises were the first to be used in upstream method dam construction with gravity flow open launders or pumps and pipe lines transporting conventional tailings slurry flows to the perimeter dam crest levels. The more coarse settled tailings materials were deposited near the disposal points with the more fine tailings slimes hydraulically routed to the interior of the impoundment to form a sloping tailings beach surface or containment cell wall.

The concept of tailings sand beach dam raises above a starter dam began in the 1910's with the use of sand declassifier boxes, that appear to be first used by Kennecott on the Barahona copper tailings dams at the El Teniente mine in Chile. The declassifier boxes allowed the larger particle sizes of wet underflow sands at the bottom of open launder chutes to drop down from elevated towers along the dam crest, while the overflow finer tailings slimes particles were routed in pipes to the interior valley containment limits. The concept of better drained and higher strength hydro-cycloned tailings sand dam raise construction started in the 1950's and continues to the present day as either upstream, centerline or downstream method raise construction.

The hydro- cyclones provide a more efficient way to separate the larger tailings sand sized particles from the finer sized slurry sands, silts and clays by the use of centrifugal force. The tailings slurry is pumped into the cyclones under low pressures to minimize pump, pipeline and cyclone wear maintenance. The centrifugal spinning slurry motion in the cyclones forces the larger sand particles to spiral to the outside toward an apex open end and drop down as an underflow sand pile, while the finer slurry materials are forced to the center of the cyclone into an attached overflow pipeline to the impoundment. An upstream method cyclone raise construction operation is shown on Figures 1 to 3.

Fig. 1: Tailings beach geotechnical investigation for dam raise

Fig. 2: Hydro-cyclone towers for under-flow tailings beach development

Fig. 3: Hydro-cycloned finer tailings slimes routed to water pool via pipeline

1.1 Starter Dam Construction

A compacted earth or earth and rock fill starter dam is constructed across the impoundment valley bottom to allow the cyclones to operate long enough at the starter dam crest level to create and maintain the minimum required sand beach width in subsequent raises for acceptable slope stability conditions.

The starter dam fill includes filter and underdrain drainage control, depending on several factors including the site hydrology conditions, foundation subgrade, and borrow materials available for dam fill. The underdrain system is isolated from the water pool area or covered with a protective filter fill layer and peripheral beach tailings for no direct hydraulic connection and overload of the underdrain flow capacity beneath the starter dam.

1.2 Tailings Beach Development

The upstream method tailings dam is raised above the starter dam in controlled dike fill benches or paddock wall raises, as required for stable perimeter tailings beach development. The tailings beach slope is dependent on the tailings slurry conditions with the primary factor being the solids to water ratio. Conventional (segregating) to thickened (non-segregating) tailings slurry flows can have beach slopes in the general range of 0.5 to 2 percent surface grades. A reduction in the tailings slurry water causes steeper tailings beach surfaces to occur at the disposal points.

The tailings beach width of importance to stability analyses for this paper is defined as the minimum perimeter impoundment width required to stabilize and support the dike fill or paddock cell raises and provide adequate exterior drainage strengths to contain the saturated lower strength interior tailings slimes and water pool. The amount of settled tailings available to form the tailings beach width primarily depends on the ratio of the tailings impoundment storage area to the dam crest length.

The single most important factor in upstream method dam stability is adequate tailings beach drainage, which requires the ability to deposit settled tailings above the impoundment water pool level (prevent submerged tailings disposal with related low density, strength, and poor drainage issues). Therefore the lowest risk upstream method dams have the water pool located away from the dam as much as practical after start up operations. In addition, the perimeter tailings paddock cells and beach surface should be allowed to dry by rotation of active disposal areas for densification and reduction of pore pressures in controlled and relatively thin hydraulic fill layers.

In the case of hydro-cycloned tailings beach development, a cyclone tower and slurry feeder pipes are constructed to elevate the cycloned underflow sand piles in several incremental raises as needed above the starter dam, until a new elevated bench level and tailings pipeline relocation is required. The incremental cyclone sand piles are spaced and staggered as needed to form a relatively uniform overall exterior dam slope. The number of cyclones and spacing varies as needed to prevent intrusion of the tailings impoundment overflow slimes contact within the minimum exterior sand beach width required for slope stability.

The exterior slope of the dam can also be a big factor in determining the tailings beach width. In cases where the dam crest length is significantly increasing with each incremental raise, a cycloned sand beach width will decrease accordingly. As an example: assume a dam has a 30 m cyclone sand or paddock cell tailings beach width with no changes to the raise construction or impoundment storage capacity. If the dam crest length should double in the next few dam raises, then the tailings beach width would reduce from 30 m to 15 m wide. This condition happens when the dam crest level is raised above the natural valley abutments to where the dam crest extends along surrounding valley ridges to become a more enclosed peripheral dam and impoundment disposal condition.

Enclosed impoundment basins typically have the lowest ratio of impoundment storage area to dam crest length. The exterior slope of tailings dams also have more of an impact on enclosed impoundments for both storage area and stable drained containment. The limitations in steep versus flat exterior dam slope geometry for tailings beach containment are illustrated on Figure 4.

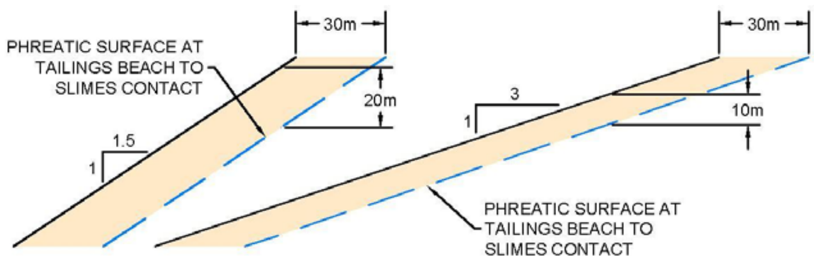

Fig. 4: Change in hydraulic gradient and slimes depth with change in exterior dam slope.

1.3 Water Pool Development

The water pool location, operational storage volume, and return water system are important aspects in the stability of the upstream method tailings dams. Most of the upstream method tailings dam failures to present day are related to excess water balance conditions (overtopping of the dam), location of the water pool at the perimeter dam limits (failure in weak slimes material or high phreatic surface seepage conditions), and gravity water return pipeline breaks or plugged and inaccessible impoundment decant towers (gravity decant towers with pipelines extending beneath the impoundment and dam limits).

The impoundment water pool is generally located in the main valley drainage or in a side valley drainage area closest to the plant site for return water flows. The impoundment water pool limits are located as far as practical away from the upstream method tailings dam to achieve the following goals: 1) minimize any direct hydraulic drainage from the water pool into the tailings beach materials, 2) deposit the low strength finer tailings slimes material away from the dam and settled tailings beach section, 3) allow drying and densification of the perimeter settled beach materials, and 4) increase the freeboard elevation from the dam crest to the operating water pool level to contain operational upsets and design storm events.

Numerous tailings impoundments use decant towers for gravity drainage in pipelines beneath the tailings dam to the present day. This practice was common into the 1980's, but is becoming less common in current upstream method dam construction, due to the higher risks of a decant pipeline break occurring beneath the impoundment or within the tailings dam foundation limits, as well as the number of decant riser towers that have plugged in the past and caused overtopping of the dam (difficult access to the plugged towers or buried pipeline collapse).

Decanting into mobile barges or land-based pump and floating pipe intake systems at the back of the impoundment are preferred for less operational risks in the return water system and easy access to the intake for maintenance and repair. The operating water pool volume should be maintained at the lowest practical level in the impoundment for both peripheral deposition to maximize consolidation and densification of the settled tailings surface and to maximize the available storage and freeboard to contain any storm runoff events within the impoundment.

In the case of enclosed tailings impoundment basins in relatively flat topography locations, a causeway access road to an interior intake tower or floating pipe and barge system is preferred to prevent the water pool from encroaching on the perimeter tailings beach limits.

IDEALIZED STUDY SECTION

1.1.1 General

The static stability analyses for this study assumed a drained and uniform tailings sand beach width with effective stress drained strengths and overall exterior slope conditions for simplification purposes. Actual upstream method dam raise slopes are benched and may have complex and variable interface contacts between saturated and unsaturated zones and settled tailings beach to slimes hydraulic fill transitions. A more detailed analyses would include dam raise benches and total stress strengths for undrained pore pressure conditions, as appropriate in designing for tailings dam materials that exhibit loading or shear consolidation at more than 80 percent saturation [2]. Vertical or horizontal wick drains could improve the tailing beach drainage and strength characteristics, where excess pore pressures are a concern.

The stability analyses were conducted with assumed circular slope failures using the Slope/W computer program developed by Geoslope. The idealized study section for finding the optimum overall exterior embankment slope angle versus sand beach width assumed 100 percent saturation of the tailings slimes adjacent to the sand beach limits, and a 30 m high overall upstream method cycloned tailings dam slope above the starter dam. The improved hydraulic drainage characteristics in steeper tailings dam slopes versus flatter slopes was not considered in this analyses with the phreatic surface assumed at the sand beach to slimes contact.

Compacted rock fill shell covers on the exterior dam slope have been used in the past to enhance the stability of upstream method tailings dams since the 1970's. A compacted rock fill shell cover was included in the analyses to show the improved slope stability conditions that can be obtained at steeper exterior slopes to closure. The rock fill shell would require a minimum 8 m width for up to 85 tonne one-way truck dumping and dozer placement operations with a 15 m width preferred for ease in truck turn around space. The rock shell width would increase as necessary for larger mine truck access to turn and dump mine waste rock fill for dozer spreading and compaction.

1.1.2 Selected Strength Parameters

The typical effective stress friction angle strengths for base metal tailings (copper tailings) range between 25 to 35 degrees and no cohesion with the lower range applicable to the tailings slimes and the higher range applicable to the tailings sand beach materials [6]. A soils strength of 35 degrees friction and no cohesion was selected for the cycloned underflows and beach material. A soils strength of 25 degrees and no cohesion was selected for the cycloned overflow tailings slimes. Typical moist unit weight densities for the fully drained underflow sand beach material were assumed at 1.9 tonnes/cu m. Typical moist unit weight densities for the saturated and less dense over flow slimes material were assumed at 1.84 tonnes/cu m. The exterior dam slopes were varied between 2.2H:1V, 3H:1V and 4H:1V to show the range of tailings beach widths required for achieving a target minimum static factor of safety of 1.5. A schematic idealized study section (overall slope without benches for simplification purposes) is shown on Figure 5.

The selected study section was then evaluated with placement of a high strength rock fill shell on a steeper 1.5H:1V exterior slope and rock shell widths varied at assumed 8 to 15 m widths. The rock fill material strengths assumed moderate compaction by haul truck traffic using locally available mine overburden waste rock stripping materials. The analyses assumed a typical effective stress dumped rock fill strength of 45 degrees friction and no cohesion [3]. The rock fill materials are defined as having more than 30 percent rock fragments retained by weight on the 19 mm square mesh screen size with less than 15 percent fines passing the No. 200 ASTM sieve size [1]. A schematic idealized study section with an exterior rock fill shell cover is shown on Figure 6.

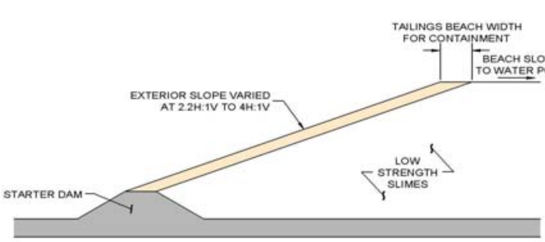

Fig. 5: Idealized study section with tailings beach containment above the starter dam

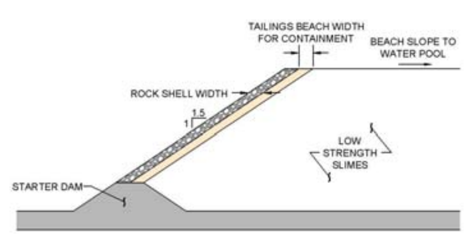

Fig: 6: Idealized study section with rock fill shell on steepened exterior dam slope

STABILITY ANALYSES

1.1.3 General

The stability analyses considered various study section sand beach and rock shell widths and slopes for developing a general pattern of curves versus static factor of safety. The dam slope geometry and strengths were simplified for comparison purposes, neglecting the affect of typical raise benches and related changes in the phreatic surface at the sand beach to slimes contact. The sand beach was assumed to be fully drained with no excess pore pressure conditions in the adjacent saturated slimes tailings. The actual operational conditions vary with phreatic conditions rising above the sand beach to slimes contact, particularly as the exterior dam slope is flattened at reduced hydraulic gradients for drainage. Similarly the tailings slimes pore pressure conditions vary depending on the rate of rise and drainage adjacent to the sand beach fill.

1.1.4 Tailings Beach vs. Exterior Slope

A pattern of curves was developed for showing the tailings beach width versus the static factor of safety (FS) for typical 2.2H:1V, 3H:1V and 4H:1V embankment slopes, as shown on Figure 7. The 2.2H:1V slope was determined from the analyses and selected strength parameters to achieve FS = 1.5 for a 30 m wide tailings beach width. The 3H:1V and 4H:1V embankment slopes were then selected for comparison to the 2.2H:1V dam slope for the range of typical construction slopes and related perimeter beach widths versus static factors of safety. The results of the stability analyses show the general trend of increased stability with wider tailings beach widths to an optimum point for each exterior dam slope at which further increases in the tailings beach width have minimal changes in the factor of safety.

Note that the dynamic analyses for the evaluation of earthquake related liquefaction would improve with wider drained sand beach widths, however the flatter tailings slopes at a given beach width would have shallower depths to the sand beach and slimes contact (less overburden confining stress above a saturated tailings zone).

Therefore the flatter exterior tailings slopes for improved static stability may actually have a higher risk for earthquake liquefaction. The liquefaction potential can be reduced by adding a confining rock fill shell on the exterior sand beach slopes, as shown on Figure 8.

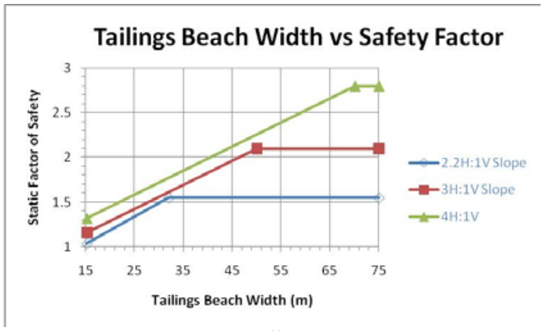

Fig. 7: Exterior dam slope affects the san beach width

Fig. 8: Rock fill shell construction on steep slope

1.1.5 Tailings Beach vs. Rock Fill Shell Cover

A pattern of curves was developed for showing the tailings beach width versus factor of safety for rock fill shell widths of 8 and 15 m, as shown on Figure 9. The rock fill shell cover allows the exterior slope to be steepened and the tailings beach width to be significantly reduced to achieve the same static factor of safety as the tailings beach without the exterior rock fill shell cover. The hydraulic gradient along the more sandy beach to finer slimes contact is also improved for better drainage and strength to reduce the risk of liquefaction.

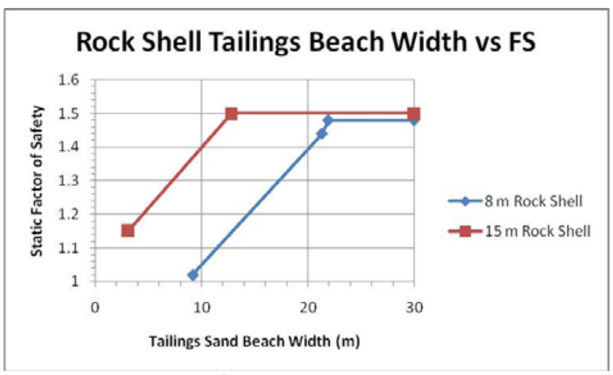

Fig. 9: High strength rock fill shell reduces beach width requirements.

As an example for the typical strength parameters assumed in this analyses, a compacted rock fill shell at 8 m width on a relatively steep 1.5H:1V exterior sand beach slope would require about 22 m of tailings beach width for FS = 1.5. The same 22 m beach width on a flatter 2.2H:1V exterior dam slope without the rock fill cover would have a lower FS = 1.2. Adding a thicker rock fill shell of 15 m for ease in construction equipment placement and turn around can reduce the tailings beach width requirement from 22 m to about 13 m on a 1.5H:1V exterior dam slope to achieve the same static factor of safety FS = 1.5. A summary of the various exterior dam slopes versus minimum required tailings beach and rock shell widths corresponding to the same static factor of safety FS = 1.5 are shown on Table 1.

Table 1: Exterior dam slope versus fill widths for FS = 1.5

Exterior Dam Slope	Tailings Beach Width	Rock Fill Shell Width
2.2H:1V 30	m	None
3H:1V 27	m	None
4H:1V 22	m	None
1.5H:1V	22 m	8 m
1.5H:1V	13 m	15 m

Conclusion

A review of typical construction practices and stability analyses of tailings beach widths for upstream method dam raises indicate the engineering design, construction and operational performance can be improved to achieve more stable dam slopes with relatively thin high strength rock fill shell covers. The upstream method dam practices and static factors of safety calculated for the idealized tailings beach study section indicate the following:

1) The amount of settled tailings beach fill available for upstream method dam construction depends on several factors with the primary factors including the mill grind size quality and quantity, the ratio of the tailings impoundment storage area to the dam crest length, and the exterior dam slope.
2) A compacted earth and rock fill starter dam embankment and foundation drain system are required at startup of tailings disposal operations to develop a minimum sand beach width at the starter dam crest level for subsequent upstream method dam raises.
3) The water pool is located as far as practical away from the upstream method perimeter dam limits to reduce the risk of low strength tailings, poor drainage and high phreatic seepage issues in the tailings beach.
4) The preferred water pool decant system is a mobile land-based floating barge pump water return system for less risk of dam instability from overtopping or pipeline breaks.
5) The optimum upstream method tailings dam slope is determined, based on the strength and drainage characteristics of the hydraulically deposited minimum tailings beach width to contain the low strength tailings slimes and water pool.
6) The effective depth from the tailings beach slope to the operational phreatic surface, as well as the depth to the low strength and relatively impervious tailings slimes contact, increases as the tailings dam slope becomes steeper.
7) The upstream method dam slope can potentially be steepened with a relatively thin high strength rock fill shell covering the perimeter tailings beach materials, which also provides a relatively erosion resistant cover for less mine disturbance to closure.

8) The stability analyses indicate the rock fill shell option enhanced tailings dam slope stability and requires less tailings beach width containment for the finer tailings slimes and water pool.

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