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The Infamous Legacy of Upstream Tailings Dams
"Because that's the way we've always done it…"

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The mining industry was traumatized by the Feijão tailings dam failure in Minas Gerais (Brumadinho), Brazil on 25 January 2019. The Feijão failure occurred a mere 38 months since the Fundao tailings dam failure (also in Minas Gerais) in November 2015, brought heightened awareness of the inherent risks associated with tailings dams constructed by the "up-stream method" to retain conventional "wet" (slurry) tailings. The Fundao and Feijão tailings incidents caused untold negative environmental impacts, more than 200 fatalities and total economic consequences to the mine owners exceeding billions of dollars. This article provides a "layman's" explanation of the upstream tailings dam construction method, its challenges, and potential consequences.

Dam Construction Methods

Tailings dam design/construction methodologies can be grouped into three fundamental categories with respect to the direction that the dam crest centerline advances horizontally as the dam crest is raised vertically (Figure 1).

All things considered, the three dam construction methods shown in Figure 1 can be considered to have a higher to lower potential dam failure risk from top (upstream) to bottom (downstream). Figure 1 shows that the upstream dam construction method results in a tailings dam crest constructed upon a larger profile of fine tailings (slimes). Tailings slimes are very fine grained, have low permeability and are susceptible to "liquefaction".

Liquefaction is a geotechnical phenomenon whereby a seemingly solid or semi-solid saturated soil mass subjected to increased pore pressure (pore pressure is the force that water occupying the space between soil particles imparts on the soil particles) morphs into and behaves as a fluid. Liquefaction can be triggered by earthquake shaking ("dynamic" liquefaction), or by a steady increase in pore pressure due to static loading, i.e. "static" liquefaction. Case studies have shown that pore pressure within liquefiable tailings have increased to a point where they overcome resisting forces (dam geometry), causing the tailings to liquefy, leading to a tailings dam slope failure. The essentially instantaneous failure is typically followed by a release of saturated tailings and water in a tailings or "mud" wave to downstream environs.

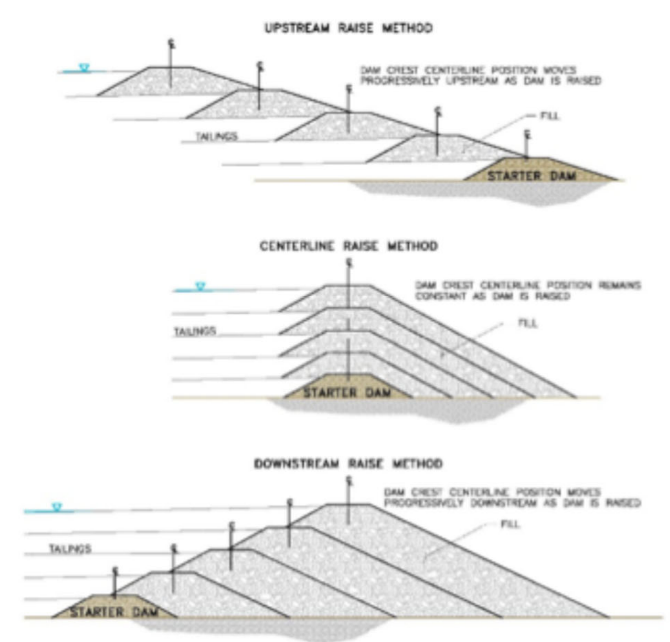

Figure 1. Upstream, Centerline and Downstream dam profiles

Upstream Tailings Dam-History

In the 1800's and early 1900's nearly all mineral extractive processes resulted in a mixture of finely crushed ore and water (slurry). A high water to solids ratio slurry allowed operators to discharge tailings from the process plant by gravity. Typically, this was accomplished by positioning the plant on a topographic high point adjacent to a waterway (stream or river). Proximity to a stream allowed operators to capture fresh water upstream of the plant, use it in the process plant, and then discharge plant effluent (tailings) downstream of the plant (typically back into the stream).

In the mid-20th century mine operators initiated the concept of tailings "storage" as an alternative to tailings "discharge". Tailings storage could be accomplished by constructing a dam in a valley and depositing the tailings behind (upstream of) the dam (much like a water storage reservoir). Opera-tors were however challenged by capital tailings dam-construction costs, which as a capital cost, which hurts the bottom line. To minimize up-front capital expenditures to construct a dam capable of storing tailings for the life-of-mine, operators looked for ways to economically initiate tailings storage, and then cost-effectively increase tailings impoundment storage capacity over time.

This ingenuity resulted in the "upstream tailings dam" construction method. Operators discovered whole tailings slurry from the plant could be separated into a course (cyclone-underflow, "sand") and fine (cyclone-overflow, "slimes") fraction at the dam using hydro-cyclones. Tailings sand (underflow) provided a free-draining "dam" construction medium, which could be used to construct an embankment to retain tailings slimes on its upstream side. Operators accomplished this by:

• Initially constructing a small ("starter") dam using locally available earthen materials near the end of a valley;

• Cycloning tailings near the starter dam and depositing the underflow sands atop the starter dam, while simultaneously de-positing tailings slimes behind (upstream) the dam;

• With time, free and interstitial water in the tailings slimes would segregate away from (upstream) the dam creating a "tailings beach" adjacent to the upstream side of the cyclone-sand dam;

• Subsequent tailings dam raises were realized by depositing underflow tailings sand atop the tailings beach to create a higher "lift" of the dam crest, behind which additional slimes were deposited to create another beach, over which a future dam raise could be constructed;

• By repeating this cycle, the dam could be raised in the upstream direction until the dam reached the full-height of the valley ridges (dam abutments) forming the valley (Figure 1).

The Legacy

Upstream tailings dam construction has been utilized for close to a century. In the mid-20th century the engineering community began to intensely study and understand liquefaction, which lead the industry towards avoiding the upstream dam construction method. In fact, several high-seismic mining jurisdictions have banned the upstream tailings dam construction method entirely (e.g. Chile and Perú). There are however those jurisdictions where the upstream method has been used for many, many generations and is continued to this day. Brazil is one such jurisdiction, and the Marianas (2015) and Feijão (2019) tailings dam failures are symptomatic of the inherent associated risks thereof.

Closing and reclaiming up-stream tailings dams will lower the risk of future failures however it is not fool-proof. The very low permeability of tailings slimes prevents them from dewatering "quickly" resulting in their re-maining saturated for decades in many cases (particularly in tropical climates where rainfall is high and low-permeability soils underly the tailings basins). The Feijão tailings impoundment was reportedly "in closure", hadn't received tailings in two to three years, and was undergoing active care and maintenance when it failed.

There are hundreds (if not thousands) of upstream tailings dams in various states of activity, or inactivity around the world (reportedly there are 88 in Brazil alone). Tierra Group is currently working at a mine in Mexico that has six upstream tailings dams on the property (five are legacy tailings storage facilities). Another Tierra Group site has three (two active, one legacy). It is Tierra Group's experience that it is quite rare to visit a mine site in Mexico more than a decade or two old that has not historically utilized the upstream dam construction method. To this end the worldwide inventory of legacy upstream tailings dams is likely unknown.

An associated concern with the upstream construction method legacy is what the author refers to as the "that's the way we've always done it…" commonality amongst these facilities. The upstream dam construction method was developed long before the advent of modern geotechnical engineering understanding, analyses, technology, and design. The author has personal experience with:

• Two separate centerline tailings dam designs (at the same mine) that were developed in the 1960's and 1970's decades without any engineering analyses whatsoever;

• A current operating tailings storage facility in Brazil whose operators stated that they were using certain design-slopes because, "that's the way they did it at a previous mine site they worked at"; and

• Being told an unaccountable amount of times over the past 30-years working in Latin America that tailings design's and operations are done the way they are because…you guessed it… "that's the way we've always done it…".

The author just returned from a site reconnaissance to a mine in South America that has been operating for more than 100 years. The latest tailings dam in operations is a single-stage earth fill dam. All previous tailings dams however were constructed by either the upstream or centerline method.

This is not to say that mining company's tailings dam designers have not advanced their engineering analytics and design expertise over the past several decades. In fact, they certainly have, by:

• Utilizing modern-day geotechnical sampling and laboratory testing procedures;

• Applying contemporary geotechnical analytical software programs; and

• Implementing new and advancing technologies (i.e. geosynthetics, drainage products, etc.) into their designs.

Quite often however these approaches are used in a highly "prescriptive" manner, which may or may not be specifically applicable in the case of upstream tailings dam construction. A case in point is the application of traditional 2-dimensional slope stability analyses to estimate factors of safety against slope instability. While traditional seepage and slope stability computer models are an acceptable industry practice for dams constructed using soil and rock and considering a phreatic surface (water level) through the dam, it is not necessarily appropriate for an upstream tailings dam where the dam crest is constructed over a "liquefiable mass" (that once liquefied be-haves like a fluid). In this case more sophisticated liquefaction and deformation analyses considering non-Newtonian flow characteristics (a media whose flow characteristics change under varying forces) of liquefied tailings may be more appropriate to understand the potential dam failure mechanism, and post-failure impacts.

Today's Engineers' Challenge

Inevitably today's tailings design engineers are asked to find ways to technically (and economically) extend tailings storage at existing (legacy) operations where upstream tailings disposal methods have been traditionally utilized. This request presents can present a myriad of challenges, including but not limited to an operator's:

• Lack of knowledge of the true environmental, social and economic risks and liabilities associated with tailings dams constructed by the upstream method (although this is becoming ever more transparent considering recent tailings dam failures);

• Cultural hesitance towards the rigors of current engineering practice required to best characterize an historic (operational or non-operational) facility prior to determining the technical and economic feasibility of its continued use;

• Lack of appreciation for the rigorous engineering analysis and design necessary to bring an existing upstream tailings dam design up to a standard of care consistent with current, internationally accepted engineering practice; and

• Pressure to maintain (or increase) production while minimizing capital and sustaining capital expenditures.

Closing

Following on the Feijão and Marianas tailings dam failures it is with a heavy heart that this article is written. To lose but one more life to an upstream tailings dam failure knowing what is known today about the associated risks is senseless. It is therefore incumbent on the engineering community to educate and advocate mine operators and regulators on behalf of society and the environment, to the risks and liabilities associated with the continued use of upstream tailings dam construction, which is why this article was written.

Tierra Group extends their sincerest condolences and heartfelt sympathy to those affected by the recent Feijão tailings dam failure near Brumadinho, Brazil.