In Defence of Upstream Tailings Dam Construction

John Phillips[1], Laila Burger[2]

[1] *Senior Technical Director, GHD*

[2] *Senior Engineer, GHD*

The majority of Australian tailings dams over the last 100 years have been successfully built using upstream construction. However, recent major tailings dam failures in some countries have led to a global industry wide review of the design and management of tailings storage facilities, with a focus on the upstream raise method as a common factor for some failures. As a reaction to the recent failures, there is the potential for regulations to become more restrictive and the potential for unjustified pressure on existing and new mines to rule out upstream raising due to possible safety and failure risks.

This paper looks at whether it is the upstream construction method or other more fundamental issues that have led to these failures and examines whether such issues are equally relevant in Australia. Does Australia have a specific advantage in being able to successfully use upstream tailings dam construction or are we fooling ourselves?

The topic of upstream tailings storage is a subject of broad and current interest and the lessons learned from historic failures are rightfully leading to improvements. Implementation of good practice starts with the overall management structure that guides how tailings dams are designed, constructed, operated and closed. Critical design practice involves understanding the unique site conditions, properties of the tailings and management of tailings placement, as the tailings form part of the overall retaining structure. Good practice during operation of upstream tailings dams is key to reducing the risk of tailings dam failures and the success of safe and sustainable closure.

This paper presents key features of both good and bad practice for the upstream raising of tailings dams and discusses how the design and operation can be made more resilient to ensure the safety of the community and infrastructure. It concludes that upstream raising can be a safe and economical method of tailings disposal if designed, constructed and operated correctly.

Keywords: *Tailings dams, failures, upstream construction, good practice*

Introduction

The upstream raising of tailings dams is usually the most economical form of tailings disposal to the present day. Embankments for early tailings dams throughout the 20th century were mostly built in small incremental raises which were constructed on the previously deposited tailings beaches. The new wall progresses inwards, or “upstream”, over older tailings. This construction technique became the prevailing raising method and still is in Australia today.

Despite the real and perceived risks, the upstream construction method remains, under appropriate environmental and project specific conditions, a safe and economical method for the development of tailings storage facilities and it is still effectively used in many countries with a developed mining industry including Australia, South Africa and China. Only two Australian tailings dam failures have been recorded on the Wise Uranium list of tailings incidents with no release of tailings. Failure rates in Australia are approximately 3×10^{-5}, per TSF per year, about two orders of magnitude less than other parts of the world. The lower rates of failure could be attributed to many of the facilities being located in arid or semi-arid environments.

Tailings dams fail much more often than water dams yet basically are using the same engineering principles as water dams. Recent failures have emphasised the devastating consequences and long term impact of a tailings dam failure.

Some tailings dams have significantly different construction than water dams and there has been a recent tendency to blame failures on specific differences such as the “upstream construction” method. However, this method has been used in Australia for over a century with no failures attributed to this cause. Out of Australia’s approx. 700 tailings dams, the majority use upstream construction. Of the two recorded Australian “failures”, one is due to visible seepage (Olympic Dam, South Australia) and the other involving foundation failure (Cadia, New South Wales). Both use upstream construction but this was not the cause of “failure”. Other Australian incidents known to the authors relate to overtopping or decant control, not upstream construction.

Tailings dams differ from water dams particularly in the duration of their construction. A typical major water dam will be built within a few years by a single contractor to a design by a single consultant/authority. A tailings dam is built progressively over 20 or more years, often by different contractors, by different consultants with different supervisors and possibly for different owners. The ultimate size is often much greater than first envisaged. Often there are changed production rates and there may be different processes influenced by different ore types. The potential for unplanned change opens the potential for error.

History of upstream construction

One hundred years ago tailings were often dumped in rivers, the ocean or across open ground and some projects still use these rudimentary processes. However, tailings dams have historically been built according to directions from the mine owner or manager who was not skilled in geotechnical engineering. Experience and/or hear-say taught them what worked and what did not. A typical operation would build a small earth wall perhaps 200 mm high by hand on the perimeter of the storage and then fill this with tailings which rapidly dried particularly in Australia's inland. This formed a firm base for the next small raise. Production rates were comparatively low and the wall could be raised in small increments on top of dried tailings, effectively as upstream construction.

The application of geotechnical principles using a geotechnical engineer did not become common place until the 1970's, some 20+ years after the same advances for water dams. The owner's team rarely had an experienced dam engineer overseeing the dam, often no civil engineer at all. Responsibility for the tailings dam was left to a production manager or an environmental officer. This has been slowly changing, with recent failures leading most mining companies to have the dam managed by an experienced civil engineer, if not a geotechnical engineer.

International failures

Following a series of devastating earthquakes, which resulted in failures of numerous tailings dams in Chile, the Chilean decree in 1970 banned the upstream construction of dams on a national level. However, most of the failed dams were constructed by the hydraulic fill method where coarser tailings were pumped to the crest of the dam and segregation ensured the coarser and free draining sandy material was dumped near the crest to form the embankment. Italy also discouraged upstream construction following the Stava tailings dam failure in 1985. The Brazilian government, in a response to the catastrophic tailings dam failures in 2015 and 2019, is also planning to ban upstream dam construction.

Most of the high profile failures with multiple casualties occurred at upstream raised dams such as Merriespruit (South Africa, 1994), Stava (Italy, 1985), Samarco (Brazil, 2015) and most recently Fundao (Brazil, 2019). The first three had other contributing factors (Fundao not yet reported). Samarco was built by hydraulic methods that differed from the more conventional earthworks construction of the others and was being raised at over 20 m per year. The design relied on creating a 200 m wide free draining zone of sand to form the outer shell of the dam.

The inability to adequately control the tailings conditions underneath the upstream raises were the main reasons for the two major failures of tailings dam in Brazil, both of which failed rapidly due to the liquefaction of the tailings supporting the outer shell of the facilities. These two cases had saturated tailings in the upstream zone which would be contrary to the original design intent. The dependency on tailings management to achieve design conditions is a specific requirement associated with the upstream raising of tailings dams.

The Newcrest Cadia Valley Operations tailings dam failure occurred on 9 March, 2018. The dam was originally constructed using the downstream method, with subsequent raises from 2008 onwards using the upstream construction method. Newcrest's Cadia Valley Operations Independent Review Board Report (2019) identified the cause of the failure as failure of the foundation due to their complex nature. Lateral movement and reduction in support helped trigger mechanism for liquefaction of the loose saturated tailings, increasing the load on the dam, already weakened by movements in the foundation. The likely cause or culmination of events was not the upstream construction method.

International response

Lessons learned from the investigations of the recent Mount Polley (Canada) tailings dam led government agencies, regulatory bodies and industry to try and improve how tailings dams are designed, constructed and operated. This led to recommendations relating to Best Available Practice (BAP) and Best Available Technology (BAT). An example of good practice is to include improved corporate responsibilities and adopt an Independent Tailings Review Board. Best practice has become extremely important within the tailings industry since the catastrophic failures in Canada and Brazil. Examples of modern and improved technologies include filtered, unsaturated, compacted tailings and reduction in the use of water covers.

It is noted that Mt Polley was not built by upstream construction and the failure is not attributed to the centerline construction that was used.

The Brazilian government response to recent failures was to ban upstream raised dams and decommission all such dams in Brazil by August 2021. Similar bans are in existence in Chile and Italy. This has raised questions here in Australia as to the future design, safety and government approval processes associated with upstream raised dams. Notwithstanding this, Australia has had standards and guidelines for the design of dams for over 30 years and the presence of engineering professionals with long careers in the industry. It begs the question as to whether the reaction to these failures is an overreaction, focusing on the upstream construction of the dam, and not the causes associated with the failure.

Recently the International Council on Mining and Metals (ICMM), the United Nations Environment Programme (UNEP) and the Principles for Responsible Investment (PRI) have developed an international standard for the safe management of tailings storage facilities (not yet available at the time of writing this paper). The review is evaluating current global practices as well as documenting lessons learned from catastrophic international failures.

The details of the standard will be defined through the review process but will at a minimum include:

1. A global and transparent consequence-based tailings facility classification system.
2. Requirements for emergency planning and preparedness.
3. A system for credible and independent assurance of tailings facilities..

The improvements to tailings design, construction and operation as a result of these catastrophic events will apply to all TSFs, regardless of construction method and is the key to effectively establishing comprehensive management guidelines that all stakeholders can adopt and apply to their operations.

Causes of historical failures

Good practice tailings deposition and management in Australia has been developed utilising the learnings from international failures and near misses. The consequences of failures have been economic loss, environmental degradation and change and in some cases loss of human life. The International Congress on Large Dams (ICOLD, Bulletin 121) reported on the main causes of tailings dam failures which included:

- Lack of adherence to the design and design details
- Poor quality control in construction due to multiple changes in staff and sometimes changes in ownership
- Inadequate water balance control and as a result, rising phreatic levels or even worse overtopping
- Inadequate foundation investigations
- Slope instability
- Erosion control
- Structural inadequacies and additional loading
- Overtopping

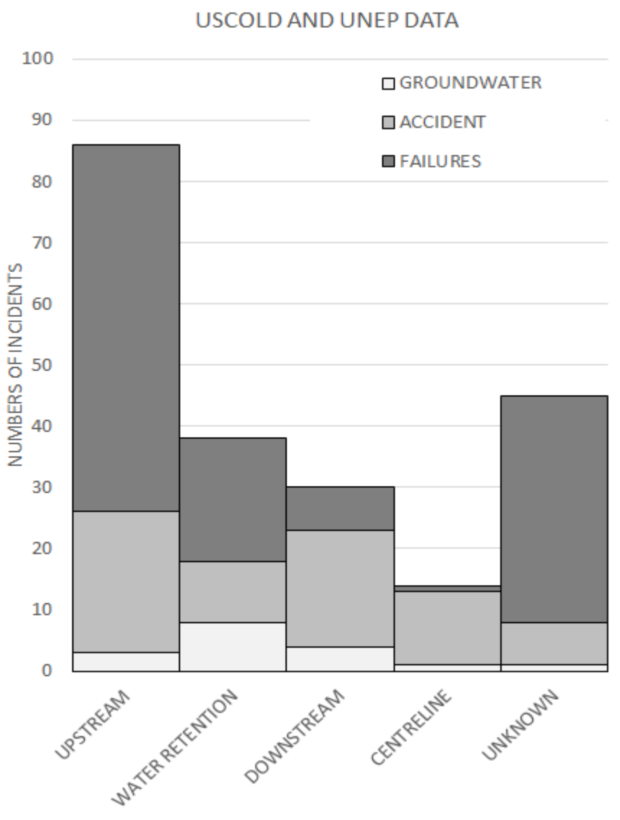

Figure 1 Comparison of tailings dam types and number of incidents (Bulletin 121, 2001)

Figure 1 from ICOLD Bulletin 121 (2001) would indicate that tailings incidents were more numerous where upstream construction was adopted, compared with downstream construction. The safest would appear to be centreline construction which had the least number of failures. However, upstream construction dams are the most common form of tailings dam and centreline construction the least common, so proportionately upstream construction may not be particularly worse.

Tailings dam construction methods

Generally, there are three main construction methods for the containment of tailings; downstream, centreline and upstream construction. Based on the writers' experience with over 100 Australian tailings dams, over 75% are built using upstream construction, a few by centreline construction and the remainder by downstream construction. A survey or 300 dams reported by Minerals Council of Australia indicated over 50% of above ground TSFs were of upstream construction.

Figure ***2*** presents the upstream, centreline and downstream raise methods.

In all three construction methods the starter embankment (Raise 1 in Figure 2) is usually constructed using earth borrow or fill/waste rock. The downstream construction method requires significantly greater volume of construction materials and hence greater construction cost compared to the upstream construction method. For any given footprint, downstream construction uses a significant proportion of the available storage for the embankment itself, leaving less available capacity for tailings storage. The starter embankment for downstream construction may be small, but subsequent wall raises are increasingly costly perhaps offset to some degree by using mine waste if not too far distant.

However, the risks associated with the upstream method has led to greater consideration of the downstream construction, despite the cost. For reasons described later, the downstream method may be the only safe choice in some circumstances.

Centreline and upstream raises use smaller volumes of select fill but may also include dried tailings material in the earth wall. Centreline raising, which is a combination of upstream and downstream raising, is also an option for the raising of tailings dams but is not commonly used in Australia. Generally, if the tailings are strong enough to support that part of the embankment built over tailings, the method could be improved to fully support the cheaper upstream construction.

The upstream method relies on the tailings behind the starter wall achieving sufficient strength to then support the next lift (Raise 2) and tailings are then filled against this raise. The process is repeated, generally using imported and compacted fill for each raise. Stability is not only dependent on the ability of the recent tailings to support the next raise but also the tailings must be strong enough to resist deep seated failure of the slope through the tailings.

A further construction method uses hydraulic fill where tailings are pumped to the crest of the dam and segregation (or cycloning) ensures the coarser and free draining sandy material is deposited near the crest to form the embankment. An outer skin is placed over this sand to control erosion. This method is sometimes described as upstream construction since stability depends on the tailings properties, but it is a significantly different method of placement. The placed material is more often saturated and loose compared to engineered upstream construction.

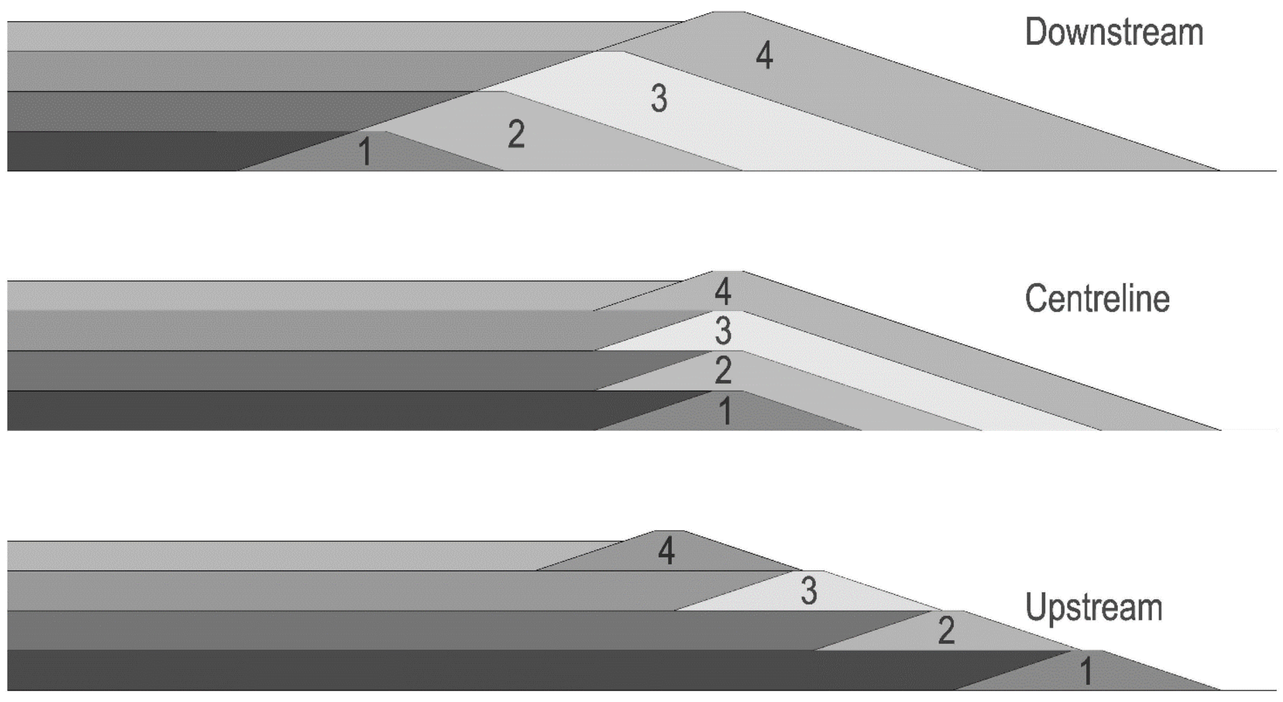

Figure 2 Upstream, centreline and downstream dam raising methods

Advantages and disadvantages of upstream construction

Generally, upstream embankment construction is most suited to arid climates, where evaporation rates exceed precipitation rates, where smaller volumes of water are required to be stored within the dam and where the pond is maintained well away from the dam wall to keep the phreatic surface low in the vicinity of the wall. These conditions ensure that the recently placed tailings are dried or consolidated sufficiently to gain the strength necessary to support the next raise. Drying can produce a significant over-consolidation pressure due to high negative pore pressures. If tailings can be kept in this partially saturated state they will retain significant strength but, even if subsequently saturated, they may retain higher strengths than normally consolidated tailings.

It is important to ensure that the coarser fraction of tailings is deposited near the embankment with no pockets of trapped slimes due to poor deposition methods.

The involvement of a suitably qualified engineer during the operation of a tailings storage facility would ensure the adherence to the key principles in design, construction and operation.

There are some key advantages and disadvantages of using the upstream raise method as discussed below:

Cost

Raising of a dam with the upstream method uses less wall material than other methods and in turn reduces haulage costs and placement costs. Typically the raise material would be external borrow material, dried tailings sourced from within the dam or from hydraulic sluicing. Cost is the main driver for most upstream tailings dam raises, and earthworks can be minimized by many small raises, offset by equipment mobilization costs and pipework relocations. The cost of each raise typically reduces because smaller volumes of material are used for subsequent raises due to the decreasing perimeter length.

While the use of dried tailings for construction reduces costs it may not be the most suitable material depending on its physical and chemical properties.

Despite the recent worldwide failures of upstream tailings dams, upstream raise methods are often preferred due to the large reduction in cost compared to alternative methods such as downstream.

Storage capacity

An additional benefit from the requirement to dry the beaches for upstream construction is that the drying increases the density of the tailings such that more tonnes of tailings can fit into a given storage volume. The excavation of dried tailings for use in wall construction increases the available volume for tailings storage. However, the excavations fill rapidly and more deeply with subsequent tailings which may not dry thoroughly and may not gain sufficient strength. Such excavations would then have to be well clear of the wall so as not to affect wall stability.

Earthworks

The upstream construction method typically uses one third to one quarter of the earthworks that would be required for downstream construction as illustrated in Figure 3. This is a key factor in reducing the amount of earthworks equipment required and the time for construction which help to keep costs low.

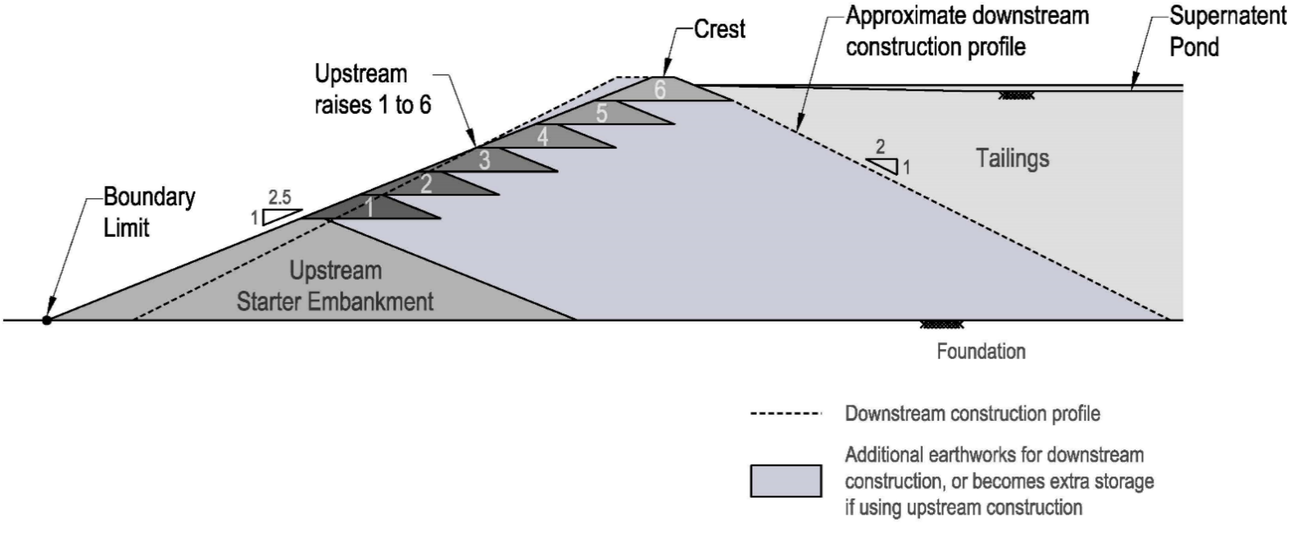

Figure 3 Increased storage volume with upstream construction (u/s section compared to d/s section)

Stability

Upstream constructed tailings dams represent a challenge in design in terms of their stability. In part this can be due to the variability of the tailings properties resulting from variations in ore or treatment processes. Segregation at the point of deposition close to the crest can deposit different particle sizes and compositions at different points making it difficult to predict behavior of these materials in both drained and undrained conditions. If the tailings are not allowed to sufficiently dry and consolidate prior to loading from the next raise, the load can increase pore pressures within the tailings and reduce available strength for geotechnical stability. In addition, a raise constructed on saturated tailings or using high moisture tailings for wall building may be more susceptible to liquefaction during a seismic event, dependent on the properties of the tailings.

The position of the phreatic line in the tailings becomes a critical item for wall stability and liquefaction. This line can be kept well back from the wall by the use of internal toe drains to collect seepage which is passed under the wall for collection. Typical slip circle locations in upstream and downstream raised dams are presented in

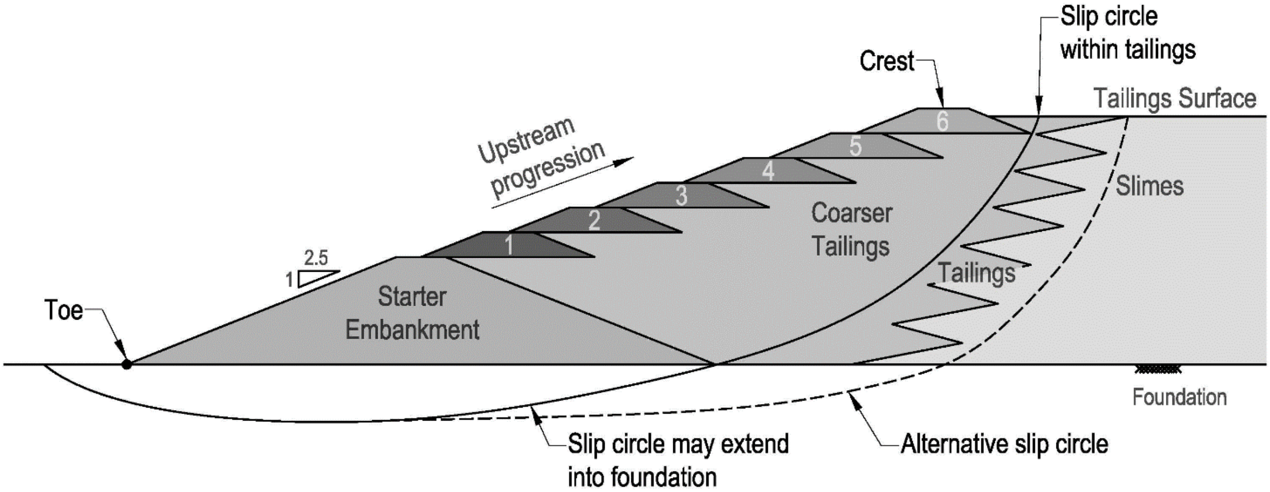

***Figure 4 and Figure 5**.*

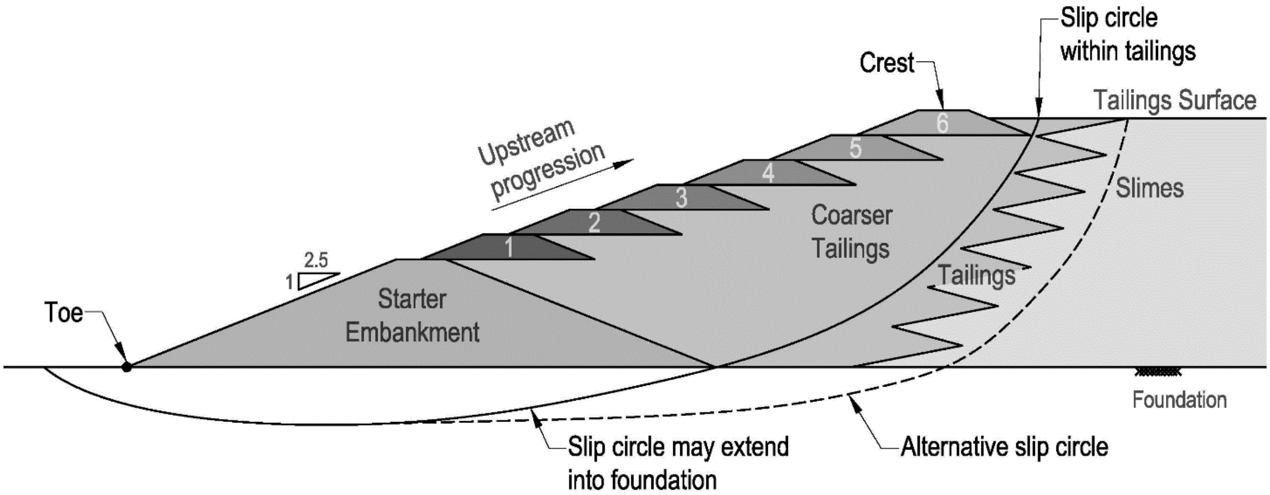

Figure 4 Typical slip circle location within an upstream raise dam

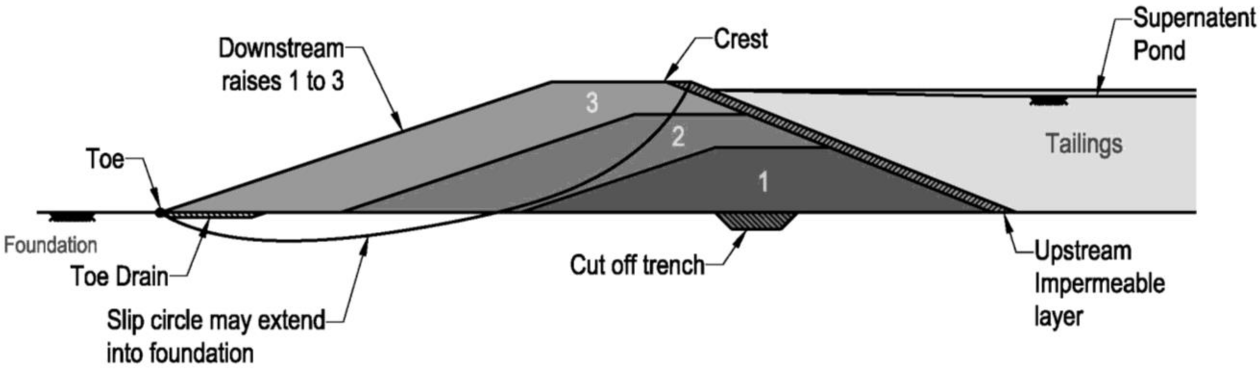

Figure 5 Typical slip circle location within a downstream raise dam

Rate of rise

Drying of tailings is key to successful upstream construction. This imposes a limit on how thick a placed layer can be and how fast tailings can be added to the surface. Upstream construction is not suited to rapid rates of filling. Enhanced drying is used on some projects using amphirols or ploughs to increase exposed drying area to increase evaporation rate.

Reliability in achieving the necessary drying can be improved by having two or more storages of sufficient area that one can be left to dry whilst the other is receiving the next layer of tailings. For very large storages, an equivalent result is achieved by slowly rotating deposition around the perimeter to leave ample drying time in inactive parts of the beach. This requirement for extra area or strict control on placement patterns may be considered as a disadvantage for upstream construction.

Water holding

Embankments built by upstream construction have little continuity between successive raises. Hence it is difficult to create a continuous watertight zone for the full height of storage. If the geometry is adjusted to achieve this, the resulting phreatic line, if used as a water holding dam, would be close to the face thus requiring flatter slopes for stability and reducing the efficiency of storage. It is important to maintain the decant pond well away from an upstream construction wall, requiring understanding and diligence by operating staff.

Types of upstream construction

The term upstream construction includes a variety of construction methods, all with the common factor of the wall being built over previously placed tailings, thus progressing in the upstream direction. Commonly used techniques include;

- Building an engineered earth wall of a few metres height over previous tailings and possibly over the previous earth crest
- Scraping dried tailings from the surface to form a wall made out of tailings on the outer perimeter
- Hydraulic sluicing from the crest, relying on segregation or possibly cycloning to form a sandy perimeter which is then shaped into a perimeter wall.

These different techniques, sometimes used in combinations, will produce walls with distinctly different properties. The first is the most controlled with known engineering properties of the fill. The latter two have less engineering control of properties. The wall material for the last technique is accompanied by large volumes of water which can keep the tailings saturated despite underdrains and the decant pond being kept away from the wall.

In Australia the first technique is common. The most common materials used for upstream raises are borrow soils (local or external to the site), mine waste rock or cycloned tailings (coarse fraction). The use of tailings, at least in part, for wall building is sometimes used. Wall building by hydraulic sluicing is rare in Australia.

Cyclones can be used to increase the rate of particle segregation for particular types of tailings with the intent of depositing coarser sand tailings closer to the embankment crest and pushing the finer slimes further away from the embankment towards the centre of the facility. The coarse material can contribute to ensuring drainage of the tailings and control of the phreatic line near the wall.

What are the risks associated with upstream construction?

The distinctive risks associated with upstream construction derive mostly from building on previously deposited tailings. These include;

- Insufficient strength of tailings to support the new construction, countered by limiting the height of the new raise and/or increasing the strength of tailings by drying or consolidation.

- Excess pore pressure in the tailings due to adding load onto the tailings, or due to continuous addition of water by sluicing for wall construction, countered by limiting the rate at which load is added or by not using sluicing.
- Limited water tightness of the wall due to there being no continuous water resistant core, countered using tailings placement patterns to ensure water cannot encroach against the wall or by complex designs.
- Liquefaction of tailings either by cyclic loading (e.g. earthquake) or by static liquefaction (changed loading conditions), thus greatly reducing the strength of the tailings that are part of the wall structure. This is countered by evaluating in the design phase and by ensuring tailings aren't saturated.

Does Australia have a specific advantage?

Australia has successfully constructed upstream raise dams for over 100 years. Improved construction practices and regulation around tailings design, construction, operation and management has been put in place for both designers and operators. ANCOLD and State guidelines have set appropriate and authoritative standards to assist industry.

Fortunately, many of tailings dams in Australia are in inland areas where evaporation greatly exceeds rainfall. This is used to advantage by;

- Placing tailings in relatively low lifts (< 1 m) and allowing to dry before adding further tailings or construction
- Having large land areas available to minimize rate of filling
- Drying to partial saturation produces over-consolidation due to stresses from negative pore pressures
- Managing the water balance to keep the decant pond well away from the wall thus keeping the phreatic line low and maximising drying on the tailings beach
- Underdrainage near wall to aid removal of water and lower phreatic line

A general rule of thumb is to limit the rate of rise of the tailings to about two metres per year, approximately the amount of excess evaporation in many projects. This necessitates having enough tailings area to accommodate the production rate within this height limit. A water balance is used to verify the amount of drying that can be achieved, considering also factors such as tailings properties and salinity effects.

The targeted result is a low saturation tailings, dried to give strength. It also means that the height of wall raising is limited to about two metres per year.

Making upstream construction resilient

Guiding principles

Good practice during design, construction, operation and closure make the process more resilient against mistakes in design, construction and operation. However, the potential risks as described in Section 9 require significantly more diligence to the principles detailed below.

Good practice is required for all forms of construction, including upstream construction, and starts with the following principles;

- Appropriate procedures, personnel and responsibilities by the mining companies
- Understanding the site conditions, which include;
  - Geological setting, with particular focus on foundation geology (for the life of mine)
  - Environmental features and proximity to inhabited areas,
  - Avoiding catchments which can add water into the tailings area
  - Seismicity, climate and topography
- The physical and chemical properties of the stored tailings
- The properties of the dam construction materials, both geotechnical and geochemical
- Consideration of closure in the design phase
- Expected capacity of the facility
- A good understanding of the expected water balance
- Appropriate construction methods
- Good pond management practices
- Avoid slimes being deposited near the embankments.

In addition to understanding the unique qualities of the project, the mining industry (government, local communities and other stakeholders) must apply the following to meet the highest standards and ultimately operate a safe and sustainable upstream raised dam;

- Correct application of the design principles
- Application of good practice principles

- Application of the best technologies
- Comprehensive monitoring and surveillance

Good practice principles

The benefits of applying good practice principles to the design, construction and operation process for an upstream raise will result in the overall better performance of the structure over time. The application of good practice will show itself in the overall stability performance of the embankments, stronger tailings, better performance of filters and in overall water management/water balance.

Preventing failure by overtopping involves close control of water on the surface of the dam and minimising the volume of water on the dam at all times It is also prudent to consider other lines of overtopping prevention, such as the construction of emergency spillways to minimise the effects of unpredicted situations arising from poor maintenance or management or from extreme storm events.

As upstream raised dams are dependent on the strength and integrity of the underlying tailings it is possible to utilise modern technologies and principles to increase the foundation strength by using mud farming practices. Mud farming allows an Archimedes screw type bulldozer (amphirol) to cut into the upper layers of the tailings and expose wet tailings for additional solar drying. This technology is an alternative technology to the conventional placement of rock fill to pre-load and increase the strength of tailing under a proposed upstream raise. The benefits of modern technologies for the preparation of upstream raising are likely to include reduced costs and increased confidence in the foundation.

The deposition of tailings in thin consistent lifts and alternating deposition between a number of TSF cells will ultimately increase tailings strength, increase consolidation and increase the density of the tailings ready for the construction of the next upstream raise within the required timeframes.

There continue to be advances in site investigation techniques such a cone penetrometer testing (CPT), static liquefaction research, 3D geophysical surveys, LiDAR, inSAR and satellite imagery. There are similar advances in remote monitoring and ability to respond or intervene remotely. Sophisticated modelling software has expanded the engineers' design toolkit.

Conclusions

A number of high profile failures has led to lack of confidence by the public and investors in the ability of mining companies to deliver safe tailings dams. Some countries have banned upstream construction as though this method is the common factor or culprit for the failures. This paper demonstrates that upstream construction is not the key trigger to failures. Upstream construction is a valid form of building a tailings storage and has demonstrated its success in Australia for over 100 years. It is not suitable for all situations and requires recognition that each TSF is unique, in a unique geological setting, subject to unique climatic events. For example, upstream method tailings dams are not suitable for seismically active areas of the world. Tailings dam designers must adopt the latest best practice guidelines and technologies.

It is not business as usual for the mining industry. The solutions to public and government acceptance of the upstream raise approach sits with the mining industry to implement good practice and apply good practice methods to upstream raise designs.

In conclusion, upstream construction can be a safe and stable tailings containment option if designed, constructed, operated and maintained in accordance with good or best practice. Understanding where the upstream method is best applied and where it is best suited is paramount in the success in providing safe impoundment during operation and for closure.

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