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Geotechnical Considerations in Designing Tailings Storage Facilities to Minimise Environmental Impact

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Summary: Disposal of tailings is commonly considered to be the single most important source of potential environmental impact for many mining projects. Increased public awareness and regulatory involvement have meant that the management of tailings is possibly the most sensitive environmental issue confronting the mining industry at present. Consequently, the design of a tailings storage facility has evolved into a critical aspect for all mining operations. This paper provides a broad overview of the key geotechnical considerations associated with environmentally responsible tailings storage facility design.

1. INTRODUCTION

The primary objective of mining is the economic recovery of mineral commodities from the parent ore. In as much as tailings are a waste byproduct of the recovery process, traditionally they were not distinguished as a separate entity with distinct and complex physical and chemical characteristics requiring experienced management. Growing awareness of mining impacts over the last decade has, however, pressured the mining industry into adopting a more responsible approach to tailings management.

The term "tailings" is derived from the fact that the mineral recovery process generates a product called concentrate at the top (or "head") and a waste called tailings at the end (or "tail"). The tailings contain crushed gangue minerals, spent process water and varying amounts of chemical reagents added during the process to enhance the recovery of the product mineral from the ore. The tailings are typically discharged as a low-density, free-flowing liquid to storage areas termed "tailings storage facilities" (TSFs).

In the past, tailings storage facilities were all called "tailings dams", as they acted as permanent hydraulic structures. The current trend in tailings management is to try and minimise the potential for environmental impact by minimising the water content in the contained tailings. Hence the preferred reference to a "tailings storage facility" rather than a "dam". A variety of tailings storage methods is available to the geotechnical designer. This paper focuses on the geotechnical design considerations for the storage of tailings behind TSFs utilising earthfill embankments.

2. ENVIRONMENTAL ISSUES

Some of the most significant, and certainly most visible, environmental impacts arising from mining are associated with the construction, operation and long-term performance of TSFs. The potential for environmental impact can, however, be mitigated with careful consideration of the following issues during the TSF design and operation stages.

- **Land Degradation** - an area of land, possibly up to several hundred hectares, will be disturbed to construct an aboveground TSF.
- **Water Pollution** - seepage of process liquor from impounded tailings can result in:
    - rising groundwater levels, possibly into the vegetation root zone;
    - contamination of groundwaters from mobilised heavy metals and/or other contaminants; and
    - acid mine drainage from the oxidation of sulphidic tailings.
- **Surface Water Impact** - the siting of an aboveground TSF will alter the hydrological regime of the area, which may affect the downstream environment.
- **Remnant Process Chemicals** - the tailings' may contain remnant traces of chemicals used in the recovery process that may be environmentally hazardous.
- **Release of Tailings** - the path of tailings from an embankment breach can extend hundreds of metres downstream, contaminating large areas.

- **Visual Impact** - the siting of a TSF will impact the surrounding landscape, particularly at closure when at full height.

- **Air Quality** - fine grained tailings can be easily eroded when dry, and when windblown may cause a dust hazard.

- **Social Impacts** - the siting of a TSF may affect the cultural, archaeological and socio-economic environment.

3. HOW SAFE ARE TSFs?

Comparisons between TSF failures and incidents at hydroelectric and water-retaining structures were documented by the International Commission of Large Dams (ICOLD, 1995). ICOLD plotted the total number of failures reported worldwide in 10-year increments for TSFs and water supply dams. The results are shown in Figure 1.

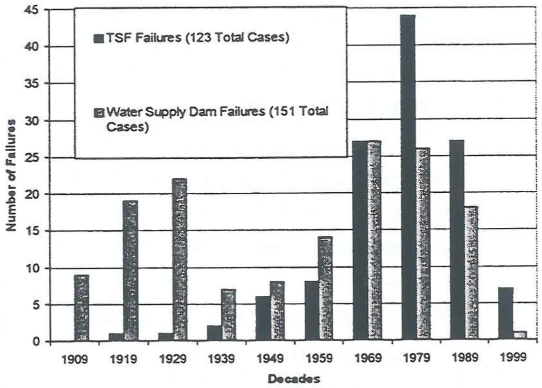

Figure 1 - Water Supply Dam and TSF Failures (ICOLD, 1995)

Even though the database is not complete, the overall behaviour of the two structure types is observed to be very similar and identifies some convincing trends. The increase in the frequency of TSF failures relative to water supply dam failures may be due to increased regulatory involvement and community awareness and hence their reporting.

4. TSF DESIGN GUIDELINES

The aim of modern tailings management is to apply sound engineering principles from a variety of disciplines related to dam, geotechnical and environmental engineering in order to store tailings safely and economically with minimal disturbance to the surrounding environment. Concern over the potential hazards associated with tailings storage has led to an increased involvement by regulatory agencies. As a result, a number of guidelines for tailings management have been developed, some of which are described below.

In Western Australia, legislative controls on tailings storage are mainly the responsibility of the Department of Environmental Protection (DEP) and the Department of Minerals and Energy (DME). To assist the designers, operators and owners of TSFs in Western Australia, the DME has published guidelines on the design, approval and operation of TSFs. Similar guidelines exist in other Australian states and territories. The Australian federal DEP has also published a series of best-practice management handbooks on mining, including TSF design and tailings management.

A number of technical bulletins covering TSF design, operation and closure have been published by the ICOLD tailings sub-committee. Readers of these bulletins, however, should be aware that, to the best of the author's knowledge, there is no international legislation that could force the application of these guidelines to Australian practice.

Whilst these publications provide the designer with guidelines and best-practice principles for sound tailings management, they are by no means prescriptive. The tailings designer must be able to apply the techniques of geotechnical analysis and engineering in association with the documented principles in order to achieve a site-specific environmentally responsible TSF. The tailings designer can apply the principles of soil mechanics to characterise the tailings and their behaviour, however, an appreciation of their difference from most naturally occurring soils is required.

5. KEY GEOTECHNICAL DESIGN CONSIDERATIONS

5.1 Tailings Characterisation

Most tailings are in the form of a fine-grained slurry with a solid fraction that behaves like a soil, however, depending upon the orebody characteristics and process type, they can vary considerably in their physical, chemical and mineralogical characteristics. As the performance of a TSF is largely influenced by the properties and characteristics of the tailings to be stored, it is imperative that the tailings' properties be determined early in the design development, and periodically reviewed during operation to optimise the TSF's performance.

Hard rock ore crushed as part of the mineral recovery process generally produces angular particles in the sand, silt and even clay-size fractions. As a result, these tailings have geotechnical characteristics more common to granular materials than to silts or clays, regardless of their particle size distribution.

Geotechnical property tests performed on small tailings samples provide a basis for comparison with other tailings and soils and enable the extrapolation of laboratory other properties. A typical suite of laboratory tests might include:

- solids content (% by weight);
- specific gravity of solids;
- particle size distribution;
- soil plasticity (Atterberg Limits); and
- liquor pH and salinity.

Results from the above tests are used to define TSF design parameters such as flow characteristics, beach slope, settling rate and storage density. The following more specialised tests can be conducted to refine the design parameters:

- Settling Test – to determine the tailings' rate of water release.
- Triaxial, Shear Box and Vane Shear Tests – to determine strength parameters (friction angle, cohesion, shear strength) for use in stability, bearing capacity and liquefaction potential analyses.
- Shrinkage Limit Test – to determine the maximum density that can be achieved by atmospheric drying alone.
- Consolidation Test – to determine the rate of water release and time dependent deformation under load.
- Permeability Test – to determine the rate at which water will flow through the tailings (used in seepage analyses).
- Compaction Characteristics (maximum dry density and optimum moisture content) – to determine the tailings' suitability for use in TSF raising works.
- Dispersivity – to determine the erodibility of the tailings.
- Mineral and Chemical Composition – to define the mineralogy of the tailings and the nature of any potential contaminants.
- Rheology Tests – to determine the tailings' flow properties.

For operating mines, production tailings are available for testing, however, if the design is for a new mine, then samples must be taken from tailings produced in laboratory scale metallurgical tests. For both cases the critical concern is obtaining a representative sample. Mine process water should be used wherever possible such that laboratory test results are representative of the tailings' behaviour within the TSF.

5.2 Tailings Storage

Surface impoundments are by far the most common tailings storage method, however, changing economic and regulatory conditions now require the consideration of more innovative deposition and storage methods. The available storage methods generally fall within one of the following categories:

- surface impoundments;
- in-pit disposal (disused open pits);
- paste backfill (underground mine stopes);
- deep water (ocean or lake); or
- river disposal.

A brief description of the geotechnical considerations for each of the above storage methods follows.

5.2.1 Surface Impoundments

Surface storage of tailings generally utilise earthfill embankments to retain both the tailings solids and liquor. The impoundment layout is selected to be compatible with the topographic setting of the site and can be either a:

- cross-valley impoundment (single embankment);
- side-hill impoundment (three embankments); or
- paddock or ring-dyke impoundment (four embankments).

Surface impoundments are formed by two general classes of embankment structure:

- water-retention type embankments; or
- raised embankments.

Water-retention type embankments are constructed to their full height prior to commencing tailings discharge, and are best suited to impoundments with high water storage requirements (such as a cross-valley impoundment with a large internal catchment).

Raised embankments are the most common type of surface impoundment structure. They differ from conventional water-retention type embankments in that construction of the embankment is staged over the life of the facility to limit upfront capital costs before the mine is in production. Raised embankments begin initially with a starter embankment sized to impound often the initial two to three years of tailings output. Subsequent raises of the embankment are scheduled to keep pace with the rising elevation of the tailings. In areas of high net-evaporation an impoundment is typically sized to store tailings at a vertical rate-of-rise of around 2.5 m/annum. The embankment raise height and schedule is determined on the actual tailings rate-of-rise measured during operation.

TSF embankments are raised using a wide range of materials, including natural soils, mine waste or tailings. The method of raising is categorised by the direction of translation of the crest as the raising proceeds. In order of increasing cost, the raise methods are:

- upstream;
- centreline; and
- downstream.

Cross-sections of the above raise types are illustrated in Figure 2.

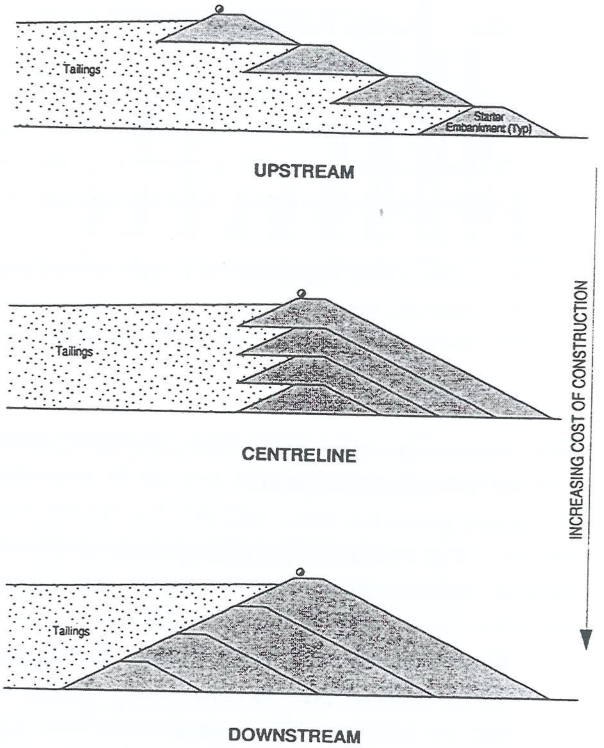

Figure 2 - TSF Raise Methods

The initially low density and strength of the deposited tailings, and their relatively slow strength increase with time, are important geotechnical considerations for the design of a TSF. Upstream raising of a TSF can therefore present some interesting geotechnical challenges as construction often utilises tailings as the fill material and the raise embankment is founded on the stored tailings.

5.2.2 In Pit Disposal

Tailings disposal into mined-out pits provides a relatively cost-efficient storage method. This alternative is attractive for many operations as it may reduce the mine owner's environmental liability by filling an otherwise deep void, however, there are a number of geotechnical issues that limit the usefulness of in-pit disposal, including:

- typically about 25% less material than was removed can be placed back into the pit;
- the pit fills at a fast rate due to the small surface area and large depth;
- the rapid rate-of-rise of the tailings results in poor consolidation, resulting in reduced storage capacity and large ongoing settlement;
- rehabilitation may be delayed many years due to the unstable tailings surface;
- there is potential for contaminant migration with hazardous tailings stored below the groundwater table; and
- tailings disposal into the pit precludes the recovery of further mineral from the pit at a future date.

5.2.3 Paste Backfill

In certain circumstances tailings can be mixed with additives (such as cement) to form a paste and discharged underground to provide structural support. Some South African gold mines have used this method since the turn of the century, however, its application in Australia has been limited.

Underground disposal can reduce the site's environmental liability as the volume of tailings to be stored on the surface can be reduced by up to 50%. The method, however, requires tailings with suitable characteristics (generally high permeability and low compressibility) and they need to be inert without potential hazard as they are likely to be stored below the groundwater table.

5.2.4 Deep-Water Disposal

A minority of mining operations discharge tailings in deep water, either into a lake or the ocean. The lack of reliable operating data available for comparison to baseline data has resulted in the public perceiving this method as “environmentally unacceptable”. However, in highly seismic, high rainfall and steep terrain mining areas or where tailings are likely to generate acids due to pyrite and other sulphides in the ore, then deep water disposal may be the only feasible method.

5.2.5 River Disposal

As per deep-water disposal, river disposal may be the only economic alternative in highly seismic, high rainfall and steep terrain areas. The degradation of the downstream environment at a number of operations has resulted in poor public acceptance of this method.

5.3 Tailings Deposition

Tailings is deposited as a slurry at water contents ranging from 40 to 200% (solids content 30-70%). Selection of the most appropriate deposition method generally depends on the tailings’ characteristics, process type, site constraints and the local climate. The available deposition methods include:

- **Cyclic Drying** (paddock rotation), where thin layers of tailings are rotated through a system of ‘paddocks’. In regions of high net-evaporation this method can provide a dense, stable tailings mass.
- **Subaerial Deposition**, which is a generic term for the deposition of tailings on beaches above the decant pond water level. This method is typically used in cyclic drying systems.
- **Thickened Discharge,** which involves thickening the tailings slurry to a solids content of up to 70% (water content 40%) to take advantage of the natural beach slope formed by sub-aerially deposited tailings, creating a tailings stack with an essentially conical shape. Thickened tailings generally beach at a steeper slope
- **Subaqueous Deposition**, which is the pumping of tailings into a liquor-filled containment. This method is typically used in areas of high net-rainfall or to minimise the acid generating potential of sulphidic tailings.
- **Co-disposal**, where the mixing of coarse and fine tailings streams produces another material with geotechnical properties superior to either of the constituent wastes.

Any of the above deposition methods may be the most appropriate, irrespective of the mineral being mined, and should be considered as part of the design development.

5.4 Site Selection

The principal criteria for TSF site selection are:

- properties of the tailings;
- distance and elevation relative to the plant;
- topography of the available terrain;
- hydrological and hydrogeological regime;
- site geology and geotechnical soil profile;
- location of ore reserves;
- lease areas available;
- regulatory requirements;
- sites of significance; and
- rare or endangered flora and fauna.

The selection of the most appropriate site is essentially a screening process considering the above criteria, commencing with a preliminary evaluation followed by a more detailed investigation and evaluation. The screening process involves the application of various constraints to an initial array of sites, which ultimately results in a much smaller subset of reasonable siting possibilities.

5.5 Geotechnical Site Investigation

A field investigation is undertaken to determine the geotechnical suitability of the proposed site for tailings storage and the suitability of local materials for use in the TSF construction. A typical sequence of events for a geotechnical site investigation would involve a preliminary desk study of aerial photographs, and geological and contour maps, followed by a subsurface exploration with sampling, field tests and laboratory testing of undisturbed and bulk samples.

In addition, for TSF upstream raising a geotechnical investigation of the stored tailings is often conducted to determine the stored tailings strength profile and assess its suitability to found the raise.

5.6 Embankment Design

5.6.1 Slope Stability

Under normal conditions a soundly designed and constructed TSF is expected to perform without excessive deformation or the threat of slope instability. The embankment could become unstable if:

- overtopped by tailings or supernatant liquor;
- high water pressure levels develop within the embankment as a result of a high phreatic surface;
- seepage through the embankment or foundation results in piping of fine-grained materials; or
- the tailings, embankment or foundation liquefy during seismic loading.

It is generally regarded that minimum long-term factors of safety of 1.5 (typically corresponding to a less than 1% probability of failure) and 1.0 (typically 50% probability of failure) represent an acceptable level of safety for TSFs under respective static and seismic loading conditions. The geotechnical factors influencing the TSF embankment stability are the:

- embankment height and slope;
- phreatic surface position;
- nature and strength of the embankment fill and foundation materials; and
- time duration of loading (undrained versus drained behaviour).

As the embankment profile and storage properties changes during the life of the TSF, the embankment stability should be regularly reviewed during operation. Sensitivity analyses for a range of soil properties and phreatic surface levels are recommended as part of the embankment stability assessment.

5.6.2 Seismicity

To be stable under earthquake loading the geotechnical design needs to take into consideration:

- the level of seismic activity (historic and predicted) at the site;
- the ability of the TSF and its foundations to survive seismic shaking;
- the potential for liquefaction of the stored tailings, embankment fill or foundations due to a seismic event; and
- the TSF siting relative to areas of habitation and infrastructure.

The following two earthquake levels are generally considered during the geotechnical design:

- the Operating Basis Earthquake (OBE) for normal operations; and
- the Maximum Credible Earthquake (MCE) for extreme conditions.

The OBE is the earthquake that is liable to occur at least once during the expected life of the structure and is often chosen as the earthquake that has a 10% probability of exceedance in a 50-year period, which is equivalent to an annual probability of exceedance of 1 in 475 (Fell *et al.*, 1992). A TSF is expected to function in a normal manner after the passage of the OBE.

For TSFs located in highly seismic areas or where failure could result in large loss of life or extensive property damage, the seismic analysis is usually based on the MCE. After the passage of the MCE, damage to the TSF is acceptable as long as the integrity and stability is maintained and the release of impounded tailings and liquor is prevented. The MCE is defined as the maximum hypothetical earthquake that could be expected from the regional and local potential sources for seismic events that would produce the severest vibratory ground motion at the site (Fell *et al.*, 1992).

Loose, saturated sands of the gradation normally produced from most mine tailings are highly susceptible to liquefaction. Tailings liquefaction results in a sudden strength loss that can have catastrophic effects should the embankment fail. Liquefaction is an important consideration for TSFs raised using the upstream technique as the raises are founded on the stored tailings. The risk of liquefaction can be minimised by maintaining the decant pond level away from the embankment during operation such that these tailings are not saturated.

5.6.3 Hydrological Considerations

Historically overtopping has been the most frequent cause of TSF failure, often a result of mis-management rather than poor design. Overtopping can severely erode the embankment downstream slope, either reducing the freeboard or compromising the stability until stored tailings and liquor are released to the downstream environment. Therefore, experienced determination of the design flood is essential. The design of a major TSF, where failure could result in loss of life or extensive property damage, should be based on the probable maximum flood (PMF).

Although the discharge of toxic liquor is to be avoided if at all possible, controlled discharge is preferable to having the embankment overtopped which could result in a catastrophic failure with the release of huge volumes of tailings and liquor.

5.6.4 Erosion Control

Erosion of the TSF embankment surface can occur due to the action of wind or water. Uncontrolled erosion can adversely affect TSF stability, either directly by modification of the embankment geometry, or indirectly as a result of the eroded material blocking drains.

Some embankment materials, such as sands, silts and dispersive clays, are more susceptible to erosion than others. Materials of this type should not be left exposed on the embankment crest or downstream slope. Tailings themselves are generally highly erodible and should be covered with a layer of waste rock if they are used in TSF raise construction. Sulphidic tailings used to upstream raise a TSF will need to be covered with a suitable barrier on the downstream batter to prevent acid mine drainage.

Internal erosion of material from the embankment resulting from seepage (commonly termed 'piping') can become a serious issue. Piping can occur when drainage measures provided to control the seepage are inadequate or when defects occur within the embankment, such as settlement cracking or poor fill compaction. Internal erosion is best managed by correct selection of construction materials, correct filter design and experienced construction supervision.

5.7 Seepage

The notion of a "water-tight" TSF is a false one, all TSFs leak. Seepage can be separated into the following two categories:

- seepage through the storage embankment or embankment foundations; and
- seepage to the groundwater mass.

Seepage of the former will in most cases 'daylight' on the embankment slope or downstream of the embankment. This can compromise the embankment stability if the internal embankment drains are inadequate. Seepage of the latter type may express itself downstream of the TSF, but is generally confined to the issues of rising groundwater table and groundwater contamination.

TSF seepage control is site-specific and should be evaluated during the design development according to the following three general categories:

- seepage barriers;
- seepage recovery systems; or
- liners.

5.8 Instrumentation

The purpose of instrumentation is to measure phenomena crucial to the behaviour of a TSF. Geotechnical instrumentation utilised as part of the TSF design may include:

- bores to measure standing water levels and to sample groundwater for chemical analysis;
- piezometers (standpipe, pneumatic, hydraulic or vibrating wire) to monitor pore pressures for stability analyses;
- flow measuring devices (V-notch, rectangular or trapezoidal weirs) to measure seepage discharge;
- settlement plates and inclinometers to measure embankment deformation;
- survey control network to accurately measure TSF movement; and
- motion accelerographs (seismographs) to record the TSF's behaviour during seismic events.

6. CONCLUSION

The long-term storage of tailings poses a significant risk to the environment surrounding a tailings storage facility. Increased awareness of the potential hazards associated with tailings storage over the last decade has led to stricter control by government authorities and increased responsibility by mine owners. As a result, the geotechnical assessment and design of tailings storage facilities has evolved into a critical aspect of mining operation. The challenge to miners and their geotechnical advisors is to use the principles of soil mechanics and geotechnical engineering in association with an appreciation of the complex behaviour of tailings to design, construct and operate a tailings storage facility in such a way that it remains safe and stable for perpetuity and results in minimal impact to the surrounding environment.

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