REPURPOSING TAILINGS STORAGE FACILITIES FOR DEVELOPMENT: EXPERIENCES IN MINING AND CIVIL APPLICATIONS

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ABSTRACT

Tailings being a waste product of mining and quarrying is highly compressible thus tailings dams and ponds are usually undesirable for development. However bigger picture issues such as sustainability and environmental considerations, and demand for land in urban or constrained areas, provide catalysts such that sites once thought of as undevelopable, are being considered for development. The question is, can a tailing storage facility (TSF) be used sustainably and productively after completion of mining? The aim of this paper is to show that it is not only possible, but perhaps now even desirable.

Several case studies of sustainable and productive end uses for TSFs are presented and discussed in this paper. A range of technical approaches are demonstrated in site investigations, characterisation of the tailings, and designing ground improvement works to allow reuse.

The first case history is a TSF in Western Sydney previously used as settlement ponds in a sand quarrying operation. Converting this TSF for industrial development involved ground treatment using a combination of wick drains and preload, as well as placement of engineered fill over the tailings. Another nearby TSF, is being developed as environmental wetlands which is a very different end use and thus the approach to its development is also very different. In mining, a case study is presented of construction of temporary mine infrastructure including crushing and screening plants, directly on top of an active tailings dam with ongoing settlements, a result of a geometrically highly constrained site. Some ground improvement was undertaken but because mine infrastructure has a relatively short design life and can be more tolerant to settlement, the improvement works were significantly optimised.

Collectively these case histories demonstrate a wide range of end uses for TSFs and the corresponding wide range of applicable ground improvement techniques and settlement criteria. The case histories emphasise that the geotechnical engineer needs to collaborate closely with the site owners and developers, and the designers of the future surface infrastructure, to allow TSFs to be repurposed with confidence and achieve sustainable outcomes. In particular we note the importance of all parties agreeing on practically achievable settlement criteria (as part of Landform Performance Requirements) and appropriate selection of the type of infrastructure, such that the repurposing is commensurate with the nature of the site.

1 INTRODUCTION

Tailings being a waste product of mining and quarrying is highly compressible thus tailings dams and ponds are usually undesirable for development. However bigger picture issues such as sustainability and environmental considerations, and demand for land in urban or constrained areas, provide catalysts such that sites once thought of as undevelopable, are being considered for development. The question is, can a tailing storage facility (TSF) be used sustainably and productively after completion of mining?

The aim of this paper is to show that it is not only possible, but perhaps now even desirable.

Several case studies of sustainable and productive end uses for TSFs are presented and discussed in this paper. A range of technical approaches are demonstrated in site investigations, characterisation of the tailings, and designing ground improvement works to allow reuse. The importance of appropriate Landform Performance Requirements for a given site which account for the practical limitations and capabilities of tailings, is emphasised. The role of the geotechnical engineer's job is discussed in nominating or agreeing on LPRs, and providing technical support in the form of site investigations, site characterisation, and ground improvement design to achieve the LPRs within other constraints. It is not intended to provide specific of extensive details of each case study; rather to highlight and emphasis some of the key aspects related to project success, in each case study.

2 LANDFORM PERFORMANCE REQUIREMENTS (LPRs)

Landform Performance Requirements (LPRs), as they are sometimes or often called, are simply a complete set of performance criteria to which the TSF repurposing is designed and constructed to achieve. Geotechnical LPRs can include:

- Total settlement limits.
- Differential settlement limits.
- The above, often need to have different limits and be nominated over different time frames corresponding to the design lives of various infrastructure, for example:
    - Structures.
    - Pavements.
    - Stormwater and other utilities.
- Bearing capacity and foundation stiffness for various foundation systems and retaining walls.
- Slope stability and slope face performance criteria.
- Pavement design and performance criteria.
- Other criteria usually specified for earthworks such as site classification.

Depending on the nature of the TSF, some of the LPRs may be set by regulatory requirements, for example ANCOLD (2019) Guidelines on Tailings Dams. If the TSF project involves a closure with a long required design life, criteria can become onerous and involve long return period events (flood, earthquake, etc). However repurposing of TSFs can often fall outside of ANCOLD / closure requirements.

There are many other non-geotechnical LPRs that are also applicable and need to be integrated with the geotechnical design. These can include:

- Final surface treatment considering things such as erosion, and vegetation.
- Drainage including surface run-off and infiltration.
- Environmental issues such as contamination and acid sulfate soils.

Broadly the process by which the authors usually approach the geotechnical aspects of redevelopment of a TSF involves:

1. Nominating and agreeing on appropriate LPRs with relevant parties. It is important that all parties understand that the performance of a TSF cannot be the same as the performance of a normal greenfield site. Realistic LPRs need to be agreed on and understood by all. Often this can involve various parties “meeting halfway”. Should the issue of landform performance not be appropriately addressed and agreed, this can prohibit a development regardless of how good the geotechnical engineering is.
2. Investigating and characterising the TSF, to the extent required. TSFs are usually recent deposits with a varied history and without any benefits of improvement in conditions accruing from the passage of geological time, and this should be considered when planning the investigation and characterising the site.
3. Designing ground improvement works to meet the LPRs, and integrate geotechnical aspects with other disciplines.
4. Constructing the works and undertaking verification and certification that the LPRs will be achieved.

The above process is not novel or innovative, but it is important that each step is done well and in a way that recognises the variability and performance of tailings.

3 CASE STUDY 1 – INDUSTRIAL DEVELOPMENT

3.1 SITE HISTORY

The first case history relates to a TSF located in Western Sydney which was previously used as settlement ponds. The settlement ponds were created as part of the sand and gravel quarries which had operated in the 1980s. The TSF occupies an area of about 40ha and was proposed to be developed as an industrial development. Converting this TSF for industrial development involved ground treatment using a combination of wick drains and preload, as well as placement of engineered fill over the tailings.

Based on the historical photographs, key features of the settlement pond are identified and listed below:

- The quarry activities began around 1986, as seen in Figure 1(a).
- Settlement ponds are observed from 1988 and the tailings have been discharged at multiple points (at least 6), as seen in Figure 1(b).
- A delta in the settlement pond could be observed in 1991, as seen in Figure 1(c).

- Capping works started between 2001 and 2002.
- Capping works finished in between 2005 and 2006, as seen in Figure 1(d).
- Ponding water observed in some areas in 2009 and 2010.
- No major change in the site between 2010 and 2020.

3.2 CONSTRAINTS AND CRITERIA

The required structure to be place on top of the TSF includes the following:

- Bulk filling up to 7m thick.
- Industrial buildings, which includes warehouses and multi-storey office buildings.
- Retaining walls at the western boundary of TSF.

The following criteria were agreed on as part of the LPRs applying to the completed landform for the industrial development:

- Total post-construction settlements of up to 100 mm.
- Local tilts up to 1 in 300, but not associated with total settlements of more than 100 mm.
- The above, applicable over a design life of 30 years.
- Working pressure of 30kPa for the slab on ground.

Adoption of these criteria meant that is was realistic to develop the site for industrial use (warehouses and other industrial buildings, roads and other infrastructure, etc).

3.3 INVESTIGATIONS

A total of 39 Cone Penetration Tests (CPTs), including Piezo Cone Penetration Testings (CPTus), were undertaken in the tailings material to understand the character of the tailings and any buried features and to assist with the ground treatment strategies. Four historical CPTs were undertaken by other consultants and were also used to characterise the material. Of note, the CPTs were used as the basis for the site characterisation and design, and limited laboratory testing was undertaken. The CPTs provided excellent horizontal and vertical coverage (“bang for buck”) without the issues that are involved laboratory testing such as sample disturbance, and number of samples required to be representative.

Dissipation testing was undertaken to understand the tailings horizontal coefficient of consolidation, C_h.

A number of test pits were also completed to understand the existing capping material and inspect the tailings material.

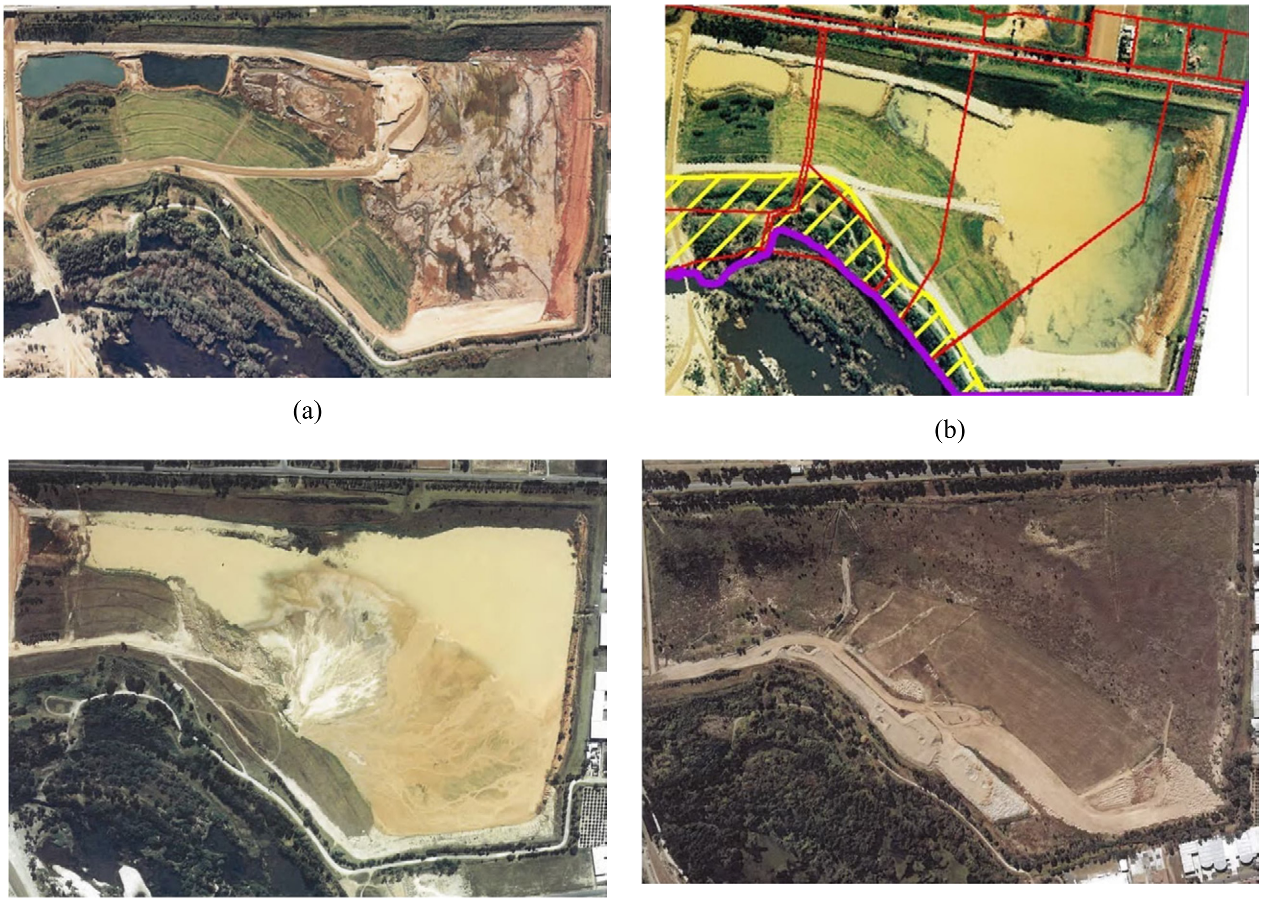
The CPTs, dissipation testings and test pits indicate the following:

- The CPTs indicate the presence of between 1 m and 2 m thickness of capping over the top of the tailings. Some of the areas particularly in the lower-lying north-east portion of the site may not have been capped as they were not trafficable during the investigation (too soft).
- The bedrock level is typically inferred between depths of 10m to 15m.
- The tailing thickness varies from less than 3m at the southern border of the site to 15m in the northern areas.
- The tailings properties range from a sandy silt to silt and clays, consistent with the mode and points of deposition.
- The transition from one end of the settlement pond to the other appears to be overall gradational and is related to the discharge arrangement and distance from the discharge point as expected for most conventional hydraulically deposited TSFs.

Combined with construction phase verification, the site investigation coverage proved sufficient to characterise the site and undertake the design.

3.4 CHARACTERISATION

Based on the results of the historical review and the results of the site investigation, the TSF was categorised into four settlement zones (i.e. S1 to S4) depending on the tailings characteristics and thickness of the tailings and any features (e.g. buried batters) that require special attention. Figure 2 presents the extent of each zone and Table 1 presents the adopted design parameters for each zone.



(a)

(b)

(c)

(d)

Figure 1: Historical photographs (a) quarry activities began around 1986; (b) settlement pond observed in 1988; (c) the delta formed in the settlement pond in 1991 and (d) capping works finished around 2005 and 2006 (NSW Government Spatial Services 2024)

We interpreted the characteristics of each zone as follows:

1. Area S1 is characterised by
    a. Presence of capping layer over most of the tailings, which comprises of gravelly sand and sand.
    b. Relatively thinner tailings (<4m) due to presence of underlying possible compacted fill riverbank embankment/cut batter and edge of dam.
    c. Indicative average corrected cone resistance 5 to 10MPa.
2. Area S2 is characterised by
    a. Presence of "better tailings", which typically comprises sandier materials.
    b. The tailings becoming deeper from south to north due overlying possible compacted fill and/or cut batter into bedrock.
    c. Thickness of tailings ranges from 4m to 14m.
    d. Indicative average corrected cone resistance 2MPa with peak value up to 4MPa.
    e. May contain thin layer of "poorer tailings".
3. Area S3 is characterised by
    a. Presence of "poorer tailings", which typically comprises fine-grained material.
    b. The tailings directly overlying bedrock.
    c. Thickness of tailings ranges from 10m to 14m.
    d. Indicative average corrected cone resistance 0.2 to 0.5MPa.
4. The ground conditions in area S4 were less well defined than other areas because access for investigation rigs was limited by the unsuitable surface conditions and ponding surface water. Based on the historical records, conditions in S4 were expected to be similar to area S3, however there was also the potential for conditions to be less favourable (i.e. greater magnitude of and slower settlements) due to the potential for increasingly clayey nature of tailings further from the main discharge points at the south end of the site.

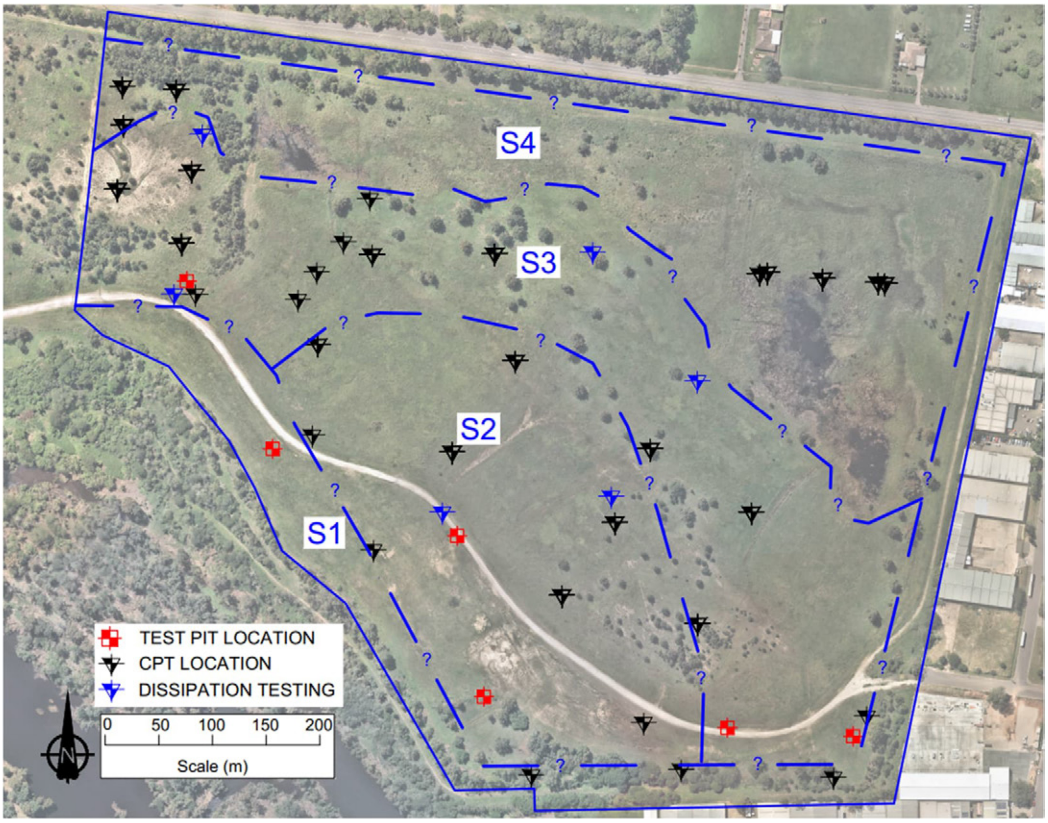


Figure 2: Plan showing the extent of four settlement zones

Table 1: Design parameters

Settlement Zone	Horizontal coefficient of consolidation, C_h (m^2/year)	Compression Ratio, C_c	Creep ratio, C_α/C_c
S1	500	"Best estimate" = 0.02 "Likely range" = 0.01 to 0.03	0.03
S2	10	"Best estimate" = 0.02 "Likely range" = 0.01 to 0.03	
S3 & S4	5	"Best estimate" = 0.02 "Likely range" = 0.01 to 0.03	

Table 2:Adopted design approach

Zone	Wick drain adopted	Permanent fill height (m)	Preload surcharge height (m)
S1	No	1 to 4	No
S2	Yes (1.5m spacing)	1 to 5	2.5m
S3 & S4	Yes (1.5m spacing)	1 to 7	3.5 to 4m

3.5 GROUND IMPROVEMENT WORKS

To achieve the required construction target timeline and the criteria listed in Section 3.2, the adopted design approach comprises a combination of the following:

- Wick drains/vertical drains. The adopted spacing is a triangular spacing of 1.5m x 1.5m connected together at the surface by horizontal drains, as indicated in Figure 3. It is noted that the adoption of horizontal drains as means of the drainage path has resulted in significant saving in cost and programme compared to utilisation of a drainage blanket as is traditionally adopted for embankment design over soft soil, but not optimal for large areas such as this site. It also eliminates the need for the wick drain to be installed through the drainage blanket which sometimes can cause negative impact on the productivity of wick drain installation e.g. when the drainage blanket is over compacted.
- Surcharge filling (preload surcharge) above the final landforms. The height of the surcharge differs for each settlement zone (e.g. S1, S2 etc.).
- The target preload period is 12 months (not including the time required for filling, and removal of surcharge). Variability in the rate of consolidation was managed by altering (increasing or decreasing) the preload period, rather than installing more wick drains.

The selection of the combination of the above is based on the tailings thickness and the design parameters, the adopted design is as presented in Table 2. The post construction secondary settlement (creep) is mainly governed by the creep rate and it determines the performance of the site over the 30-year design life. The creep rate adopted on the analyses was based on empirical data. There was a possibility that the creep rate may vary across the site, some areas might have higher creep rate than the design assumptions. he wick drains and surcharge are only adopted when the thickness of "poorer tailings" exceeds a total of 2m. Figure 4 shows a schematic diagram of the adopted design approach.

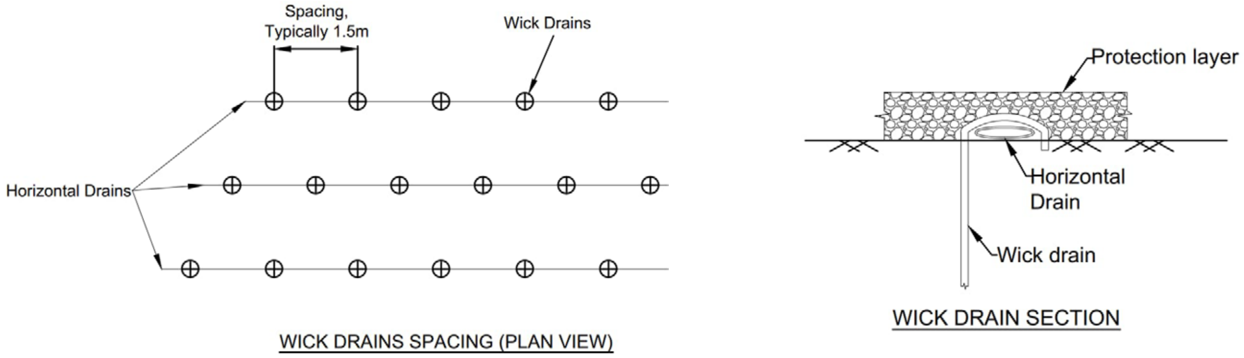


Figure 3: Typical wick drains and horizontal drain arrangement

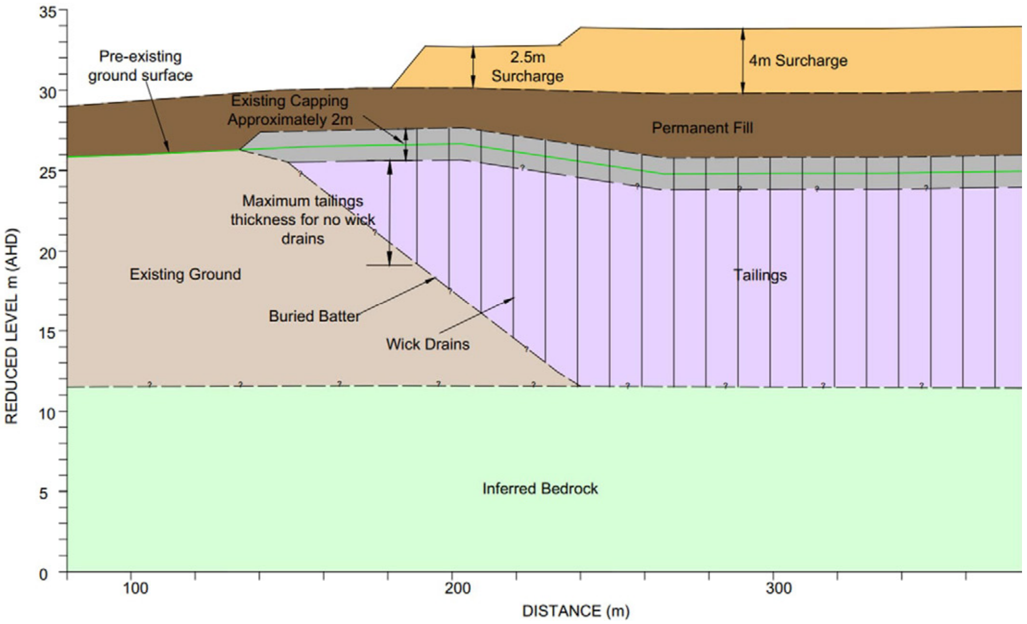


Figure 4: Schematic diagram showing the design approach

Figure 5: Aerial image at the start of the ground improvement works

3.6 DESIGN VERIFICATION

To validate the design predictions and maintain the slope stability during construction, a combination of the following instruments is adopted:

- Settlement plates.
- Surface settlement pins/markers.
- Vibrating wire piezometers.
- Wick drain penetration resistance as an indicator of tailings compressibility, refer to Salim et al. (2024).

The proposed development discussed in this section was undertaken in stages; this provided further opportunity to optimise the design of later stages by utilising the monitoring results of the early stages. The monitoring data, including the actual filling rate, was used to back-calculate the average compression ratio on each settlement plate locations.

Figure 6 presents an example of comparison between the predicted settlement during the design phase, the actual settlement based on monitoring results during the construction and the updated settlement predictions adopting the actual placement of fill (time and thickness) but still with the original design parameters. Figure 6 shows an example where the actual settlement is toward the lower end of the "likely range" of assessed settlement. Across the entire site, the back-calculated parameters were typically found to be within the range of design parameters, as presented in Table 1.

Additionally, the preload thickness was reviewed across the later stages by taking into consideration the back-analysed compression values, while maintaining the post-construction settlement criteria. This process provided an opportunity to reduce the surcharge height and preload duration where possible.

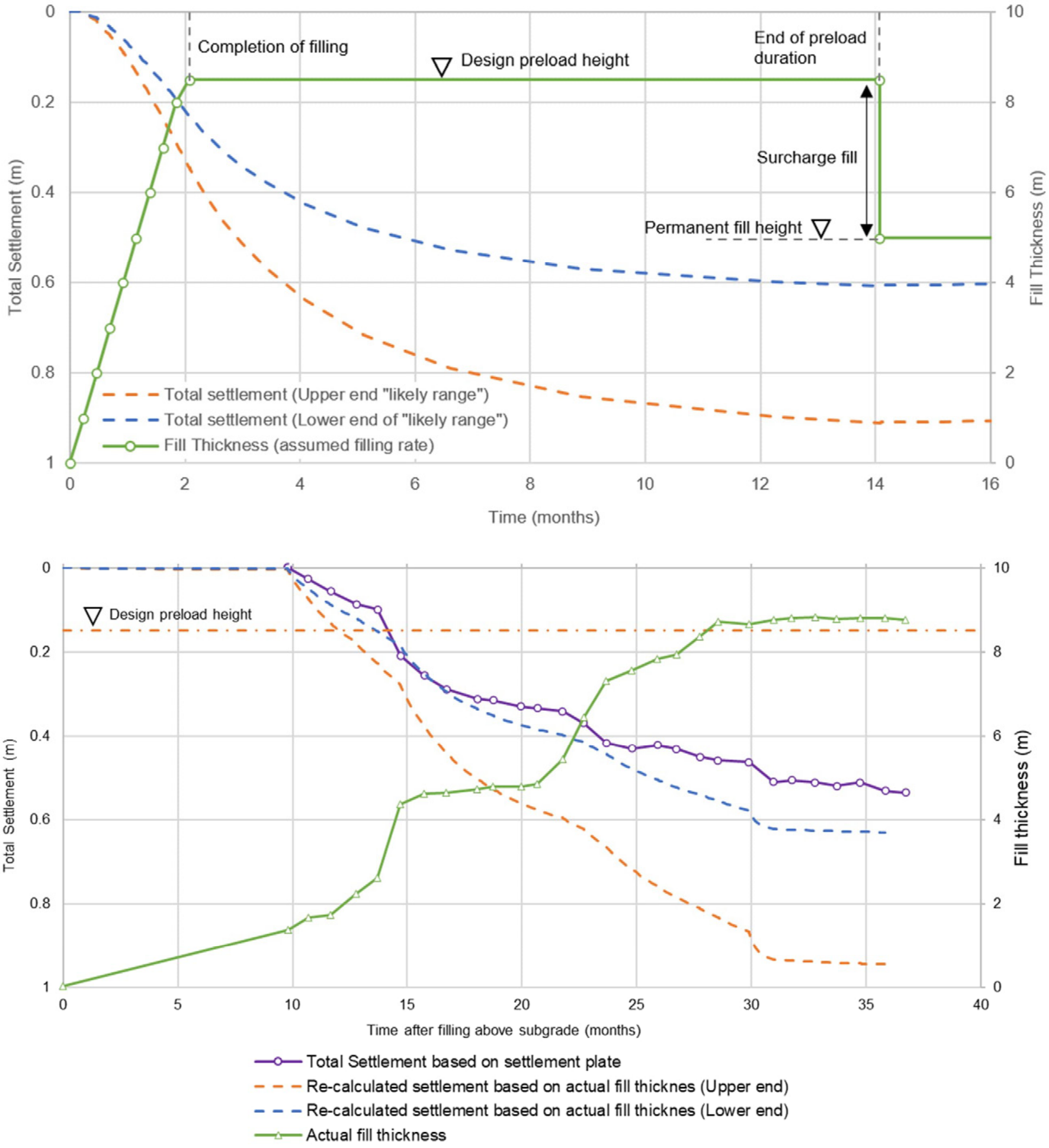


Figure 6: Comparison between (top) predicted settlement during design and (bottom) actual settlement based on monitoring results and re-calculated settlement based on the actual filling

3.7 SUMMARY

This TSF would have been unsuitable for industrial development without any ground improvements. The ground improvements at this TSF were undertaken by means of wick drains and preload to achieve the required LPRs. Selection of realistically achievable LPRs was important to ensure that the project could realistically be undertaken.

Collaboration with the contractor allows the construction to be performed in stages and thus providing an early monitoring results which gives an opportunity to optimise the design of later stages. Monitoring results were used to validate the design predictions and inform if any design changes are possible during construction (e.g. shorter preload duration, change in preload height). This was especially relevant given the large size of the site.

4 CASE STUDY 2 – ENVIRONMENTAL WETLANDS

4.1 SITE HISTORY AND PROPSOED DEVELOPMENT

Another nearby TSF, is being developed as environmental wetlands which is a very different end use and thus the approach to its development is also very different.

The proposed development comprised reshaping of the surface and construction of finger embankments to result in environmental wetland for treatment of surface water runoff from neighbouring future industrial and residential developments. The maximum embankment batter height proposed was 4.5 m.

4.2 LANDFORM PERFORMANCE REQUIREMENTS

The key to the efficient and effective redevelopment of these tailings area for use as a wetland was definition of the appropriate LPRs congruent with the proposed long term landuse.

The particularity of the proposed long term land use as a wetland was that firstly, the landform had no strict requirements on long term deformations, and secondly the landform was subject to a well established ongoing maintenance regime which included regular inspection and allowance for remediation of the embankments where poor performance resulted due to settlements, local slumping, and/or erosion. Particular emphasis was placed on maintenance in the early stages of wetland use whilst vegetation was established as part of the erosion and sediment control.

On the above basis the long term LPRs were defined as:

- Ensuring overall long term stability of the embankments infrastructure, and
- Where possible reduction of the likelihood of excessive maintenance during operation.

4.3 INVESTIGATIONS

The nature of the proposed works required access to small portions of the tailings surface, in effect only in the areas where minor excavation works or construction of finger embankments were proposed. The very soft and inundated condition of the tailings surface further constrained the ability completed intrusive investigations at the site. Further given the agreed LPRs it was deemed that a detailed understanding of the tailings conditions at depth was not required.

On the above basis a targeted investigation was undertaken which included:

- A desk top review of the tailings deposition operation.
- A site inspection
- Shallow dynamic cone penetrometer tests to test the thickness of the desiccated crust.

4.4 CHARACTERISATION

From the above the site was characterised as follows:

Site History – During the quarry operations, the area of the proposed wetlands was used as a tailings storage area. The previously excavated quarry was backfilled with tailings. Tailings comprising of silt and clay and fine sands have been deposited by subaqueous deposition over a number of years. Some areas were then capped with sandy tailings or other fill material. Subsequently some fill embankments were constructed over portions of the tailings' areas. The area had already been in use as a wetland and as such large portions of the site had been submerged by shallow ponds.

Surface and Subsurface Conditions – Based on the site observations and investigations the following conditions were assessed to be present at the Site:

- Natural soil or fill embankment.
- Sandy capping present only at some locations.
- Desiccated crust. This is the area of clay and silt tailings that have been above pond level for sufficient time to be affected by drying and thus the upper 50 - 200 mm present a higher strength than the underlying soft tailings.
- Soft tailings. These are clay and silt tailings, normally consolidated and presenting very soft to soft consistency. The desiccated crust and the soft mud are typical of a swamp area.
- Ponds. These are the areas which were submerged at the time of the inspection.

A plan showing the nominal extents of the different surface zones is presented in Figure 7. A schematic cross section of the typical site conditions is shown in Figure 8.

The natural soil and fill embankments, the areas comprising sandy tailings and the areas where a desiccated crust was present, where accessible on foot.

Figure 7: Plan image showing typical surface conditions

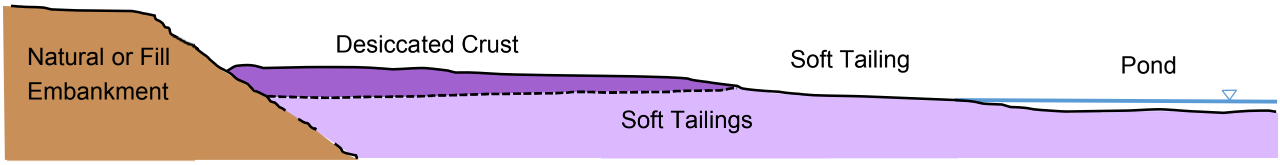


Figure 8: Cross section schematic of observed site conditions

4.5 THE BUND DESIGN

4.5.1 Zoning

Given the site conditions and the LPRs and in order to minimise the need for high quality fill, it was proposed that the bunds be constructed as a zoned embankment as shown in Figure 9.

The bund zoning consisted in a higher strength internal embankment and lower strength batters. The aim of the approach was to:

- Facilitates access for the plant during construction and for ongoing maintenance with a strong core, but also
- Allow the use of more marginal materials won from the cut works in the outer embankment.

Figure 9 presents the zoning of the different material to be used in the bunds and the basic geometry for the bunds.

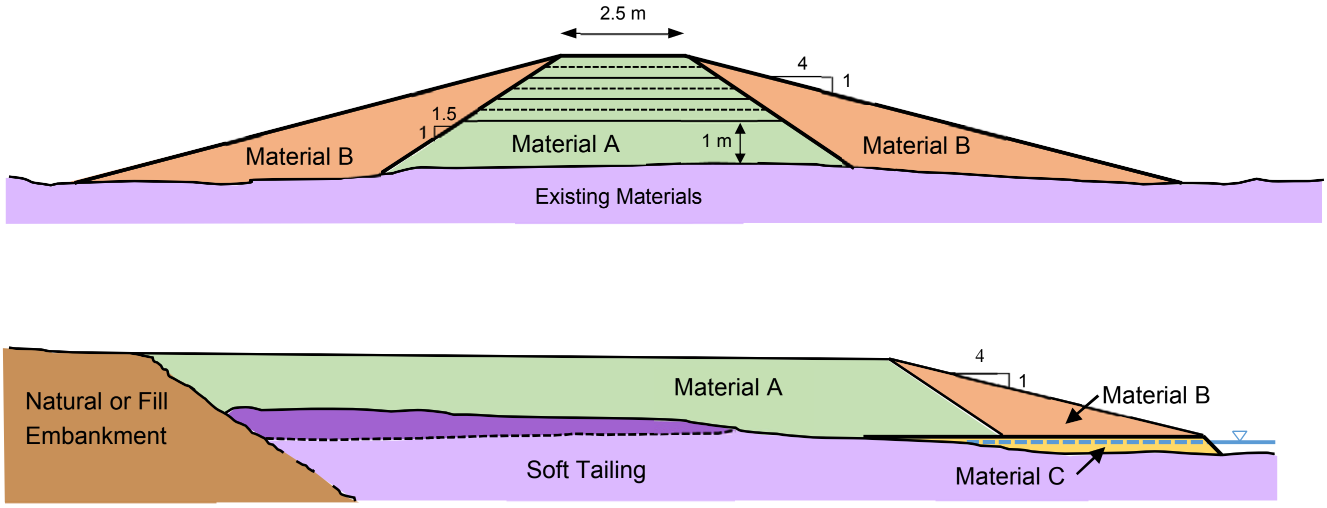


Figure 9: Material zoning in the bunds

It was proposed that the construction comprise the following steps:

- Initially a 1 m layer of imported fill or good quality site won fill (Material A) would be pushed in front of the plant to form a base for the embankment. Where ponds are present on site, a bridging layer comprising of granular imported material may have been required to form this base layer (Material C).
- Secondly, the rest of the internal embankment could then be constructed using Material A placed and compacted in layers.
- Lastly, the outer batters could be constructed with lesser quality material (Material B) placed with a lesser degree of compaction.

This approach was developed collaboratively between the contractor and the geotechnical engineer, to address both geotechnical stability and bearing capacity issues, as well as construction practicality.

4.5.2 Materials

Three (3) different materials were recommended for the embankments at the design stage. The characteristics of these materials and sources are discussed below.

- Material A (Core of the embankment): Potential sources of this material are:
    - Imported Virgin Excavated Natural Material (VENM) – Both shale, clay and sandstone are likely to be suitable materials.
    - Site won:
        - Natural or fill material from Embankments – This material could be trimmed off existing embankments within the site.
        - Capping and/or Sandy Tailings – Where capping or sandy tailings are encountered these could be reused.
- Material B (Batters):
    - Material A is suitable for use as Material B,
    - Desiccated tailings caps,
    - Soft tailings if allowed to dry, contractor should satisfy themselves that the tailings are able to dry in a timeframe suitable for the project.
    - Final surface should be protected against erosion and scour, which might include allowance for the re-vegetated surface
- Material C (Bridging layer):
    - Imported Virgin Excavated Natural Material (VENM) comprising of Sandstone fill or other rockfill sourced from site.

4.5.3 Placement requirements

Given the difficult founding conditions and the targeted performance requirements that included the need for long term maintenance, an approach to placement that allowed use of small equipment with little compactive effort was developed by the geotechnical engineer in collaboration with the contractor. The requirements adopted at design stage are listed below:

- Zone A and Zone C - Core Embankment:
  - Embankment fill shall be placed in near horizontal, laterally extensive layers of uniform material and thickness, deposited systematically across the work area. The lower layer can be up to 1.0 m thick. The maximum compacted thickness of subsequent layers shall be:
    - Either be 200 mm with tracked plant, or
    - 400 mm with proper compactor.
  - The fill shall be placed, and track rolled by at least 4 passes of an appropriately sized plant.
  - The moisture content of the fill when placed shall be assessed visually to be within 3% of optimum moisture content.
  - Temporary batters for the core embankment shall be no steeper than 1.5H:1V.
- Zone B – Batters:
  - Permanents batters shall be no steeper than 4H:1V and less than 4 m total height.
  - Material B shall be placed using suitable dozer and lightly compacted by tracking with tracked plant.
  - The moisture content of the fill when placed shall be assessed visually to be within 3% of optimum moisture content.

4.5.4 Trafficability

At design stage it was considered appropriate to pass the details of the plant selection and earthworks methodology development to the earthworks contractor who are experts in completing the works. This is because the general construction methodology including the zoning, placement, and materials had already been agreed by the geotechnical engineer. Further, safety in design requirements and any residual safety issues were clearly communicated. In order to assist the contractor completing the works some additional guidance with regards to the trafficability of the ground was provided.

The advice provided to the contractor is shown below:

- Trafficability on top of existing embankment and sandy capping should not present any issue for normal earthworks plant. The trafficability on the desiccated crust material might be achieved with wide tracks and lightweight plants, please note that the underlying subgrade is likely to be of soft to very soft consistency. Trafficability on top of wet tailings or where water is ponding is unlikely to be possible for plant. Bridging layers are likely to be required to provide a platform where small plant could work from.
- The choice of construction plant remained the responsibility of the contractor and it was recommended that the contractor visit the site prior to the start of the project in order to understand the site conditions.

4.5.5 Erosion Recommendations

It was recommended that the designer of the civil work adapt its design landscaping, erosion and scour protection requirements to account for the material zoning and compaction presented above including allowing provisions for batters to be revegetated to improve local stability and limit erosion or scour.

4.6 CONSTRUCTION EXPERIENCE

The earth bund construction used predominantly site won material with a mix of natural, existing fill and capping or reclaimed capping or sandy tailings material. Some small volume of site won river cobblestone and imported shale fill was used locally.

The initial earthwork contractor attempted to spread the material in a thick layers, pushing the material in front of the plant with a dozer to form the bund and then lightly compact the bund by trafficking (D5 dozer, 20t excavator and dump truck), see Figure 10. This approach worked relatively well in the drier and sandy parts of the tailings, but encountered issues where wet and soft clay tailings were present.

Figure 10: Earthworks moving equipment used initially

In these areas the use of relatively heavy machinery and the works starting at the end of a particularly rainy season, led to settlement of the bunds, some localised instability and formation of "mud wave", where the placement of fill material displaced the tailings underneath, with some of the tailings being displaced out in front of the advancing fill as a "mud-wave" (refer to Figure 11). This made this initial approach unfeasible for this particular design (although often "mud-waving" can be an appropriate construction technique.

Figure 11: Formation of "mud wave" and local instability during construction

This led to a revision to the plant being used on site, with smaller earth moving plant, e.g. a smaller excavator, a bobcat and a swivel tipper (see Figure 12) being selected as the earthworks plant. This increased the construction time, and allowed the tailings to consolidate and gain strength as the bund was raised. Undertaking the works during the drier season was also helpful. The method allowed the local instability, cracking and settlement that had been experienced to be remediated and the bund to be constructed generally in accordance with the specification requirements.

The final outcome (Figure 12) is a landform that is suitable to be used as a wetlands with accessible bunds which will require regular maintenance, particularly in the first few years of operations as localised settlement occurs and locally overstep batters experienced some localised slumping.

The construction highlighted the following critical factors when completing these types of capping activities:

- The earthworks contractor needs to visit the site and appreciate the site conditions and potential construction difficulties during the pricing process. Selection of appropriate equipment and scheduling of works is critical in successful implementation.
- It is important for geotechnical engineers to consider and communicate the construction risks involved especially in capping and mud-waving, and where required provide specific geotechnical advice design to cover the construction staging and methodology; particularly as necessary to meet safety in design obligations.
- The owner needs to include some flexibility in the expected delivery times and final outcome to allow responsiveness to the complex site conditions and weather effects.
- The key construction decisions are selection of plant and scheduling of works. The use of smaller plant appropriate for the site conditions and adopting slower construction timeframes allowed work in the soft tailings areas to be completed.
- Ongoing regular maintenance particularly as vegetation is established and initial settlement and strength gain occurs is an essential part of the works.

Figure 12: Revised plants with the construction of one of the bunds and some mud-waving halfway along.

4.7 SUMMARY

The purpose of an environmental wetland is well suited to a decommissioned TSF. However, unless appropriate LPRs are adopted, the design and construction may not be practical. At this site, the LPR definition was largely qualitative, ensuring that the site could be practically developed without prohibitive cost but still meeting the required end performance.

5 CASE STUDY 3 – MINE INFRASTRUCTURE

5.1 BACKGROUND

This case study is from the Ok Tedi mine in Papua New Guinea, and involves the construction of temporary mine infrastructure directly on top of an active tailings dam with ongoing primary and secondary consolidation settlements. Some ground improvement was undertaken but because mine infrastructure is temporary works, the ground improvement works were significantly optimised compared to if the infrastructure was permanent with a longer design life.

Panchalingam & Piccolo (2022) have previously presented a paper focussing on the site investigation and characterisation and this previous content is only briefly summarised herein. This paper focusses more on the site constraints and criteria, the LPRs, and the various types of designs undertaken with the corresponding ground improvement works.

5.2 CONSTRAINTS AND CRITERIA

The Ok Tedi crusher relocation project was a result of a highly geometrically constrained site within the mountainous surrounds of the Ok Tedi mine. The only location physically available for the new crusher plant was an existing active tailings dam, which also happened to be the only flat area in the vicinity, see Figure 13. Hence this was not a question of “is it feasible” rather “how can it be done”. The tailings were up to 30 m deep within an infilled valley.

Required infrastructure to be constructed on top of the TSF included:

- Crushing and screening plants,
- Stockpiles and a reclamation tunnel,
- Retaining walls and slopes.
- Bulk filling up to 22 m thickness, to raise and flatten the ground level. This filling would cause significant consolidation of the tailings. Conversely in places the filling was as little as a few metres, which presented its own challenges such as achieving adequate working platforms and bearing capacity.

LPRs included:

- Design life of the infrastructure of up to 15 years.
- Achieving a raised and flat ground level to provide a platform for the infrastructure of sufficient area.
- For “primary” structures (crusher, screening plant, towers) total settlements not exceeding 50 mm. This necessitated foundations to rock including driven piles where required, although these piles were as much “ground improvement” as structural foundations, see below.
- For “secondary” structures (tunnel, conveyor, workshops, switch room) much higher settlements of up to 200 mm were permissible. This criterion was important in enabling a practical approach to the design and construction of filling and ground improvement; tighter criteria would have made the development unfeasible.

5.3 DESIGN

The design to achieve the LPRs at the site included the following (Figure 14):

- Placement of a rockfill working platform across the surface of the tailings by pushing the rockfill out onto the TSF and in doing so displacing some of the poorest surficial portions of the tailings (called as “mud-waving” approach).
- Earthworks bulk filling and construction of retaining walls and slopes to form the final landform geometry. The specification for the filling was tailored to the ROM (run of mine) material that was available. The filling needed to be sufficiently slow so as to achieve stability of the retaining walls and 2H:1V batters (which had a combined height of up to 22 m).
- Installation of driven pile foundations in specific areas (beneath where “primary” structures were located over tailings). These piles were not directly connected to the overlying structures; a rockfill load transfer platform separated the two. The benefits of this included providing more spatial coverage of the foundations, and smoothing out any differential settlements whilst keeping within the settlement limits. This design required close engagement with contractors, and the structural engineer.

This design was achievable because of the site-specific LPRs adopted, and would not have been possible otherwise.

Figure 13: Aerial photograph of the TSF where the crusher plant was to be situated

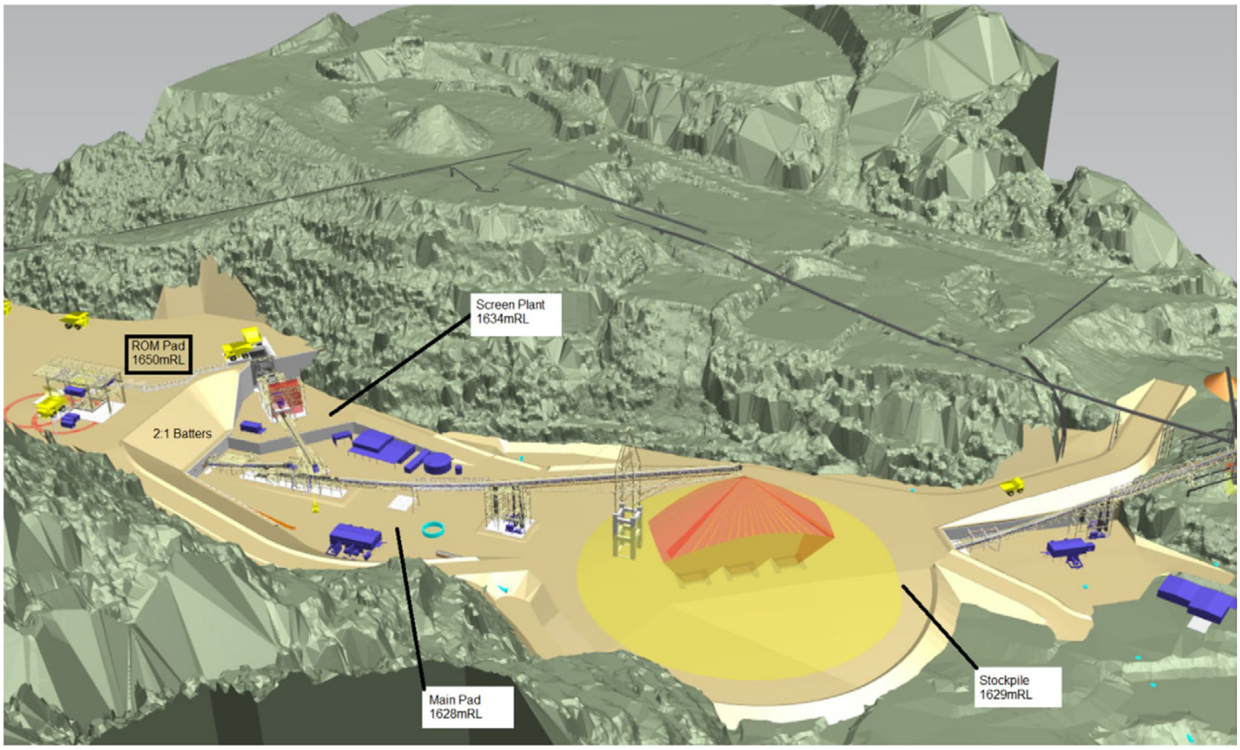


Figure 14: Overview of the TSF, with filling complete, and the new infrastructure under construction

5.4 CONSTRUCTION AND VERIFICATION

The adoption of the rockfill for mud-waving had several functions and benefits for the construction, including displacing some of the poorest quality surficial tailings, providing a limited amount of preloading to strengthen the tailings somewhat prior to construction of overlying works, and providing a working platform and confinement over top of the tailings. This mud-waving was an integral part of the design and construction, and was undertaken using a method specification with performance-based outcomes, rather than being subjected to a strict specification. “Failures” were permitted (and in fact desirable as it meant that weaker material was being displaced) during the mud-waving process provided that they did not impact safety. See Figure 15 for a photograph of the mud-waving works in progress, with the tailings displacement in front of the rockfill being obvious.

Geotechnical inspections were undertaken during construction. Monitoring included vibrating wire piezometers and settlement monitoring, see Panchalingam & Piccolo (2022) for an example of the monitoring results. The site was successfully filled and developed (Figure 16).

Figure 15: Mud-waving in progress

5.5 SUMMARY

Being a mine site, this project was focussed on operational outcomes. This meant dealing with the reality of the tailings characteristics by adopting LPRs that were not overly restrictive and allowed the use of a range of design approaches and available materials that may not otherwise have been possible, whilst still achieving the required performance over the (shorter than usual) design life.

Figure 16: Overview of the TSF, with filling complete, and the new infrastructure under construction

6 CONCLUSIONS

Collectively these case histories demonstrate a wide range of end uses for TSFs and the corresponding wide range of applicable ground improvement techniques and settlement criteria. The case histories emphasise that the geotechnical engineer needs to collaborate closely with the site owners and developers, and the designers of the future surface infrastructure, to allow TSFs to be repurposed with confidence and achieve sustainable outcomes. In particular we note the importance of all parties agreeing on practically achievable LPRs and appropriate selection of the type of infrastructure, such that the repurposing is commensurate with the nature of the site.

The case histories demonstrate that provided appropriate LPRs are agreed, TSFs can be successfully repurposed for a wide range of different developments. Geotechnical engineers, developers, and other parties are encouraged to think "outside the box" when it comes to defining LPRs, because this has a huge effect on the ability to practically and cost-effectively repurpose TSFs for sustainable end use. For example, can settlement criteria be matched to realistic expectations of landform performance and infrastructure requirements. This also applies to the design and construction, for example in the three case histories presented the initial stages of construction involved forming a capping layer or working platform by bridging or "mud-waving". This was an integral part of all three designs but method specifications and performance-based criteria were adopted rather than a typical more onerous earthworks specification. Application of a more rigorous specification to the initial filling may have precluded practical development.

CRediT authorship contribution statement

David Piccolo: Writing – original draft, Writing – review & editing. **Stephanie Salim:** Writing – review & editing. **Jeremy C.W. Toh:** Writing – original draft, Writing – review & editing.

7 REFERENCES

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