Placement of caps on soft and fluid tailings

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ABSTRACT

This paper describes a concept for placing a cap over soft or fluid tailings deposits using a floating platform for hydraulic cap placement, and compares it to two standard cap placement methods: 1) mechanical placement using earthwork equipment and 2) hydraulic beaching. Hydraulic placement from a water platform has a number of potential uses in the mining industry to manage tailings, and may be one of the more cost-effective methods to consolidate soft tailings in locations where strength is too low for land-based cap placement methods. Supplementary elements, such as installation of wick drains or other drainage features to aid consolidation can be deployed from a water platform as well. General costs of construction are compared to illustrate the competitiveness of water-platform-based capping approaches. Placing caps hydraulically from a water platform can be an alternative to other methods of dealing with fluid tailings (such as centrifuging and thin-lift drying). It offers opportunities to reduce tailings related-risk and closure liabilities, and can prove more practical and more cost-effective than land-based methods, particularly for capping very soft to fluid tailings.

1 INTRODUCTION

Tailings produced during mining and mineral processing operations often include a fine portion that accumulates as soft or fluid tailings. These fine tailings may not consolidate and strengthen in a timeframe suitable for reclamation. Large deposits of such soft and fluid tailings can be very difficult and costly to address. One of the lowest cost solutions is to contain the tailings in a mined-out pit below a water cap, but regulatory and environmental impact constraints may not allow that solution for all or even a majority of the fine tailings. If the fine tailings have sufficient strength, they can be capped and reclaimed with soil cover and vegetation for reclamation of the mine site. Even then, the tailings must reach an acceptable state of consolidation to support the landforms and maintain the drainage patterns of the reclaimed site – a requirement that may necessitate accelerating consolidation and dewatering if the tailings are soft or fluid when capped. When soft and fluid tailings cannot be capped, they may have to be dewatered using other means, often an expensive proposition in which the tailings must be removed and physically or chemically processed ex-situ rather than being managed in place. Thus, new alternatives for cost-effective capping (and tailings strengthening) technologies would be attractive for managing soft and fluid tailings.

The long-term risks associated with very soft and fluid tailings in above-ground impoundments are increasingly being viewed as unacceptable, especially in a closure landscape. For instance, the 2015 Tailings Management Framework for the Mineable Athabasca Oil Sands in Alberta, Canada calls for fluid tailings to be in a ready-to-reclaim state not later than 10 years after mine closure. In general, there is increasingly an expectation that no materials in a fluid state should be left in above-ground impoundments after mine closure.
The Dutch have been dealing with issues of capping soft or fluid sediments in order to reclaim land and remediate environmental contamination for decades, and some would say centuries. In the process, Dutch engineers and dredging companies have advanced certain technologies and techniques for capping from a water platform in order to consolidate very soft and fluid fine-grained sediments and contaminated sediments (such sediments are in many ways similar to tailings). The Canadian oil sands industry has started exploring the applicability of these solutions to their fine tailings inventory. Capping soft tailings and fluid tailings from a water platform may be useful in other mining, mineral processing and industrial waste applications as well. Mining and mineral processing that use dispersants in their process – such as the oil sands, phosphate processing, and some gold processing technologies – can accumulate large volumes of very soft or fluid tailings that are very slow to consolidate and strengthen. These industries may well find some aspects of this approach that would be of benefit in their tailings management because capping from a water platform can extend the range of tailings that can be capped to the low end of soft tailing strengths, and even into the fluid tailings range. Note: For the purposes of this paper, soft tailings are defined as having a peak undrained shear strength below 25 kPa and a fines content above 50%, and fluid tailings are fine tailings with a peak undrained shear strength below 2 kPa.

This paper compares the technique of placing a cap from a floating platform to two standard cap placement methods: 1) mechanical placement using earthwork equipment and 2) hydraulic beaching. Somewhat greater space is given to description of capping from a water platform, as it may be unfamiliar to the audience. Advantages, disadvantages, and limitations are noted for each technique.

2 PLACING CAPS MECHANICALLY

Caps can be placed on soft tailings mechanically (using earthwork equipment) working from the perimeter of the tailings basin pushing a lift of cover over the tailings, as shown in Figure 1. Generally the equipment must be low ground pressure and is often smaller capacity than is typically used in mining operations. As the cover thickness grows with successive lifts, larger equipment can be used. In general, this method uses standard fill placement methods, although careful control of lift thickness and construction practices is often needed when covering soft tailings.

![Figure 1: Placing a cap mechanically](image)

Key design issues for this method are stability of the tailings, trafficability for construction equipment, and haul distance from the borrow source for capping material to the tailings basin. Various undesirable consequences can result from tailings instability, including “mudwaves” forming at edges of the cover during placement, horizontal squeezing of the tailings, tailings bursting/boiling upward through the cap as shown in Figure 2, plunging of the cap into the tailings (for instance at a weak point), and rotational failures of the tailings. When fill displaces the underlying tailings, fill volumes increase, and the displaced tailings must be managed another way.
Trafficability is generally addressed by removing the water overlying the tailings so a crust can develop on the tailings surface (either by drying or freezing), using geo-fabric and/or geo-grid, use of low-ground-pressure construction equipment, use of lightweight fill, or a combination of these approaches. The initial lift thickness is controlled by the strength of the underlying tailings. If needed, consolidation aids such as wick drains can be placed once the cap can support the necessary equipment traffic. As with any cap placement over soft tailings, careful design and pilot testing is needed to establish the lift thickness and time for the tailings to gain strength reliably.

Wells (2010), Pollock (2010) and Abusaid (2011) provide an example of how earthwork equipment can be used to cap near-fluid materials using a combination of low density fill, geo-fabrics and geo-grids, winter placement, and wick drains. However, this type of approach is more costly and labor intensive than customary mechanical placement.

3 PLACING CAPS USING HYDRAULIC BEACHING

Caps can be placed on soft tailings deposits using traditional slurry transport methods with beach-based discharge. In hydraulic cap placement, it is usually preferred to remove the water cover over most of the tailings, and it may be advantageous if a crust has formed over the soft tailings before cap placement. A slurry of sand and water is discharged, as in Figure 3, to flow over the tailings, forming a cover as the sand settles out of the slurry. The slurry water is generally recovered for reuse.

Typically, this method requires altering the process used to place the tailings deposit so the properties of the cap differ from those of the underlying deposit. For example, tailings can be cycloned, and the coarse underflow can be used as capping material. Alternatively, deposits that have segregated during deposition can be selectively “re-mined” to obtain materials with properties that are favorable for capping.

A key design parameter for the cap is the placement slope, which controls stability during construction. While predicting beach slope is an imprecise science, key factors such as slurry density and flow rate can be varied to influence slope. Subaerial beaches are flatter than subaqueous beaches. The use of spigots can also be used to manage deposit slopes. Instability of
the underlying soft tailings in response to the sloping beached cover can be a serious complication. If the cover displaces or mixes with the tailings rather than covering them, the displaced tailings will then have to be managed separately.

Slurry fines content is also a key design parameter. Excess fines can reduce cap strength below values required for trafficability, can require rehandling when they are deposited at the distal end of the beach, or both. Another key design parameter is the gradation of the coarse material. A well graded (poorly sorted) material will segregate, resulting in variable cap properties that depend on the distance from the discharge point.

Placement methods can be planned to improve control over hydraulically placed capping material. In addition to relatively uncontrolled beach deposits, caps may be placed in controlled cells or by “controlled beaching”. With controlled cells, dozers are used to push up berms to contain the slurry flow. A spill box can be used at the discharge end of the cell to control flow and promote deposition within the cell. It is possible to densify the cap by tracking with dozers. This approach provides more control over cap placement, but requires enough strength in the underlying tailings deposit to support the cell lift thickness, the berms for subsequent lifts, and any equipment working within the cell. With controlled beaching, lateral containment berms are used, but the discharge end of the cell is open-ended. This allows more control of cap placement than uncontrolled beaching, but less than cell construction. Strength requirements are similar to cell construction.

4 PLACING CAPS FROM A WATER PLATFORM

Placing caps from a water platform is a technique by which caps can be placed using the controlled spreading of aggregate (e.g., sand, coke, gravel, etc.) from a barge or boat, illustrated in Figure 4; consequently in this approach, the water cover is retained or even deepened over the tailings to provide a water platform. The required water platform depth is typically about 2 metres. This technique has been used in sediment management to cap very soft materials – even sediments so weak they are fluids with less than 25 Pa strength (0.5 psf). However, sediment strengths generally have been in excess of 100 to 200 Pa -- stronger but still in the fluid range. Successively thicker lifts of sand are placed as the tailings consolidate and strengthen. This technique takes advantage of 1) the water platform access to the full extent of the soft tailings so the cap can be placed uniformly and homogeneously, 2) the reduced unit weight of the sand under water to avoid overloading weak tailings, and 3) the absence of trafficability issues on the cap during its construction. It also leverages the potential to use high-production-rate slurry transport of the capping sand. Once a sufficiently thick cap has been placed, the water cover is removed, and the tailings gain additional strength, after which reclamation can proceed (Costello, 2010; Jacobs, 2012).

Capping from a water platform can be performed using one of two primary methods, referred to in this paper as raining and rainbowing. Both of these techniques involve placing the aggregate (sand) cap material through the water column, which reduces the velocity of the particles and allows the initial cap layer to build gently. Raining involves placing the cap material into the water column through a device or technique designed to diffuse the slurry energy to allow the sand to gently rain through the water column and onto the soft or fluid tailings “surface.” Rainbowing involves discharging sand slurry through a water cannon, allowing the sand to spray into the desired area, as shown in Figure 5. Rainbowing is often a complementary technique to raining, used when the water depth is insufficient for the draft of the barge or when a very thin layer of sand is needed. The water cannon can spread a very thin layer of sand over a large area efficiently, while allowing the barge to travel at slow speeds that avoid problematic disturbance of the tailings deposit. Rainbowing can also be used from the shore – and for very small basins may allow cap placement without a barge or boat. Rainbowing has higher energy than raining but allows caps to be placed on soft or fluid tailings with limited overlying water depth.
Both raining and rainbowing deliver aggregate (typically sand and sometimes gravel or other specialty materials) to the water platform, usually by pumping slurry through a floating pipeline. Some placement techniques involve transport of dry aggregate to the water platform using barges. The cap material source may be a borrow pit, stockpile, separation process discharge, or material dredged from a beach. In any case, the objective of placing caps from a floating platform is to carefully control the cap material delivery rate and slurry energy to place a laterally continuous uniform cap layer with a consistent thickness. The initial cap layers are typically quite thin to minimize overloading the fluid tailings and limit the development of excess pore pressures in the tailings, with successive cap layers increasing in thickness as the tailings strength increases. Soft tailings have higher strength than fluid tailings, which allows placement of thicker lifts, with less uniformity required, than fluid tailings.
When capping fluid tailings, it can be advantageous to use light-weight aggregate, or even manufactured light-weight materials in the initial layers. An example from the oil sands is the use of coke as a light-weight aggregate. Even using the comparatively disruptive hydraulic beaching cap placement technique, coke has been observed to rest on top of tailings that have aged and gained some density (BGC, 2010). Raining coke from a water platform offers the potential to form the cap over even lower density tailings. Fluid tailings remain a challenging material to cap, and success depends strongly on experience, specially trained personnel, purpose-designed specialty equipment, and the knowledge, models, and monitoring techniques to predict and control the cap application and adapt deployment procedures to effectively and efficiently build the cap. In addition, when capping fluid tailings as an alternative to expensive removal and treatment technologies (e.g., centrifuging or thin-lift drying), it may be desirable to install wick drains or provide other drainage enhancements to accelerate strength gain in the tailings. Wick drains can be efficiently installed from a water platform, as shown in Figure 6, so there is no need to wait until the water has been removed from the basin and vehicle access is established. Boskalis, a Dutch dredger, has an illustration of how a combination of wick drains and a sand cap might look underground after installation, shown in Figure 7. The addition of wick drains can result in significantly faster consolidation of the tailings, generating water for re-use in the mine, and creating additional storage volume that could be used for tailings disposal.
Cap placement from a water platform has been shown to be highly adaptable and flexible enough to use in a wide variety of locations and conditions. The equipment and techniques have been refined and improved during the two decades these methods have been in use. This approach to cap placement has been used to contain and consolidate contaminated sediment, as well as to consolidate soft sediment to facilitate development at a number of locations around the world, see Table 1. While the engineering and construction techniques to implement this approach have been refined, development of the theoretical underpinning explaining its success is still catching up with the practical application (Vermeer, 2012; Beuth, 2014). To the authors’ knowledge, this technique or a surrogate has been tested on oil sands tailings at bench scale, in a large outdoor column (3 m diameter), and a field trial (Dereniwski, 1993), but not at pilot or commercial scale.

Table 1. Some examples of caps placed from a water platform.

<table>
<thead>
<tr>
<th>Site</th>
<th>Sediment Surface Shear Strength (kPa)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hiroshima Bay, Japan</td>
<td>0.5</td>
<td>Ling 1996</td>
</tr>
<tr>
<td>Matsushima Bay, Japan</td>
<td>0.1</td>
<td>Ling 1996</td>
</tr>
<tr>
<td>Lake Biwa, Japan</td>
<td>1</td>
<td>Ling 1996</td>
</tr>
<tr>
<td>Stryker Bay, USA</td>
<td>0.3-0.8</td>
<td>Hedblom 2002</td>
</tr>
<tr>
<td>Anacostia River, USA</td>
<td>0.5-1.0</td>
<td>Reible 2004</td>
</tr>
<tr>
<td>Soda Lake, USA</td>
<td>0.2-0.5</td>
<td>Thompson 2003</td>
</tr>
<tr>
<td>KPC Ward Cove, USA</td>
<td>0.14-4.8</td>
<td>Verduin 2002</td>
</tr>
<tr>
<td>LA Harbor Dredge Disposal</td>
<td>0.4-0.6</td>
<td>Verduin 2002</td>
</tr>
<tr>
<td>LA Harbor Cap</td>
<td>0.2-1.0</td>
<td>Verduin 2002</td>
</tr>
<tr>
<td>Ijburg Project, Netherlands</td>
<td>0.7-1.0</td>
<td>Leeuw 2002</td>
</tr>
<tr>
<td>Mocks Pond</td>
<td>Low</td>
<td>Thompson 2003</td>
</tr>
<tr>
<td>Hudson River, USA</td>
<td>Avg. 1.0</td>
<td>Verduin 2005</td>
</tr>
<tr>
<td>Melbourne Philip Bay, Australia</td>
<td>0.025-0.06</td>
<td>Jacobs 2012</td>
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One element of capping from a water platform that is very different than other capping methods at a mine is handling the water cap. Early planning for water management is important due to the volume of water to remove (and potentially add to initially form the correct depth of water platform). It is unlikely the water can be discharged into a public water body without expensive water treatment. Consequently it is important to consider early in the capping planning process where the water can be reused or stored to ensure that the capacity of the reuse and/or storage location is ready to receive the water when removal is needed.

Capping from a water platform can be expected to compress the tailings, which may increase the clear water cover depth over the tailings by more than the added sand thickness of the cap. This effect can be used to advantage during mining operations. The timing and progression of removal of the water platform can be used as another control on the loading of the soft tailings. Lowering the phreatic surface in the cap increases the effective load on the underlying tailings, promoting consolidation. Approaches to removing the water could include installing drain tile or other water conveyance (such as a coarse-grained layer with strategically positioned pump intakes) during cap construction.

After reclamation, water remaining in the aggregate cap will be predominantly process-affected water that was in the basin when the cap was placed or expressed water from the consolidating tailings and, as such, will likely exceed any discharge standards applicable to natural water bodies near the mine site. In addition, process-affected water will likely be problematic if it discharges to the wetlands, ponds, lakes and streams constructed in the final reclamation landscape, due to the presence of metals, organics, TDS and other chemicals that may limit the ability to support the necessary abundance and diversity of flora and fauna. With some forethought, the drain system that was installed during cap construction and used to remove the water cover after cap placement may be used after reclamation to intercept and direct this process-affected water away for storage, treatment or re-use.

5 KEY COMPONENTS OF A SUCCESSFUL CAP ON SOFT TAILINGS

Each of the cap placement methods discussed in this paper have advantages and disadvantages, depending on the specific application of capping technology and whether the site-specific conditions favor one method or a combination. Operators should carefully consider all the conditions and locations that will require placement of a reclamation cap to allow adaptive management using one or more of these methods to accomplish the total cap system desired for long-term reclamation. It is possible that the solution will include two or more of these cap placement methods on the same mine site and even within the same basin.

6 CAP DESIGN CONSIDERATIONS

Thoughtfully designing the cap systems to be installed in each area of the mine site, including a detailed monitoring and measurement program is important so that the caps perform as needed to facilitate site reclamation. The cap design should include an adaptive management plan that describes how measurement data and observations are incorporated into decisions to modify means, methods, placement rates, or measurement frequency/density, with site-specific criteria determined based on data quality objectives.

Analyses, lab testing, and pilot tests would likely be needed to establish both the cap thickness that can be achieved, and the strength gain that will reliably develop. An important early component to designing a successful cap on soft or fluid tailings is to model the expected consolidation behavior of the tailings after capping based on tailings hydraulic conductivity and compressibility characteristics as they change with void ratio. These characteristics can be strongly affected by mineralogy, gradation, soil structure (e.g., flocculation or coagulation), and water chemistry. For mechanical or beaching cap placement, rheology (especially as relates to shear – e.g., squeezing behaviour) can play a critical role in cap failure. While tailings may exhibit some differences from natural or contaminated sediments, particularly in soil structure
and water chemistry, the physics, test methods, and analyses needed to design their caps are the same. Liquefaction potential of caps needs to be considered, and may require mitigation depending on the likely consequences during or after construction of the reclaimed landscape. Geotechnical data obtained in the robust measurement and monitoring program implemented before, during and after construction of the cap are used iteratively with model results to refine consolidation predictions and account for tailings heterogeneity. This iterative modeling and measurement approach used in conjunction with an adaptive management plan is used through final landscape and closure design.

7 PLANNING FOR RECLAMATION

Caps provide the base for final reclamation land surface and drainage systems. The constructed caps need to be designed to be thick enough to provide safe trafficability for the earth moving and other equipment used to construct the final closure surface. The thickness of cap material placed should consider the planned landforms and likely end land uses for the tailings basin. For instance, with hydraulic placement and placement from a water platform, it may be efficient to place excess material during cap construction, and subsequently reshape it to the desired landform than to place the minimum needed cap thickness and then import more material to construct the reclamation landscape. Site-specific evaluations of materials availability, sequencing, equipment, and so forth will strongly influence these decisions.

Capping from a water platform can offer several potential benefits when integrated into tailings management planning. Placing sand layers within a tailings basin during operations can be used as a “progressive reclamation” strategy (Derenewski, 1993). Sand layers will allow the underlying tailings to consolidate as new tailings are added over them, in effect increasing the quantity of tailings a basin can contain, and releasing additional clear water for recycle. Placing the sand layers from a water platform allows managing the differing beach slopes for tailings and sand. This tailings placement strategy facilitates progressive reclamation by providing a nearly-reclaimed basin by the end of mine operations, and also reduces the volume of process-affected water to manage during and after reclamation. Boskalis, a Dutch dredging firm, has developed this concept for capping from a water platform and given it the name “Sandwich,” illustrated in Figure 8. The sandwich concept has been successfully implemented from a water platform for land reclamation in Singapore (Lee, 1987), and also using mechanical capping of frozen flue gas desulphurization sludge during the winter at a power plant in North Dakota (Solseng, 2010). Operational approaches for applying a water-based Sandwich system will be site-specific, according to the number of tailings basins in operation simultaneously, the flexibility of discharge locations around the basin(s), the supply of capping materials or sand, and other tailings management constraints of the mine.
Another potential application of capping from a water platform is in upstream dyke construction. One of the challenges with upstream dyke raises is the relatively weak material on the basin side. By placing sand layers at intervals vertically as the basin is filled with tailings, the foundation conditions on the upstream side can be considerably improved. Unlike traditional construction techniques, capping from a water platform can safely access the upstream side, despite very weak tailings, to place sand layers.

8 COST CONSIDERATIONS

The cost of placing caps with earthwork equipment tends to be strongly dependent on site-specific conditions, but is often assumed for planning purposes to be in the $5 to $15 (US) per cubic metre range. Costs may be considerably higher when capping tailings in the very soft to fluid range. Based on the experience in capping sediments, it should be expected that capping from a water platform will cost $10 to $20 (US) per cubic metre of placed sand, with the costs toward the higher end of the range for smaller areas or very soft-to-fluid tailings. Where technically feasible, and depending on material availability, the hydraulic beaching approach can be 3 to 4 times less expensive than other customary techniques (BGC, 2010). However, for capping fluid and perhaps very soft tailings, hydraulic beaching may displace rather than cover the tailings. In such cases, the potential advantage of the water platform approach can be significant. In some cases the access and flexibility advantages may be attractive enough that water-based cap placement should be considered even where tailings are not very soft or fluid.

One potentially attractive application for capping from a water platform is as an alternative to other fluid tailings dewatering technologies. In this application, vertical drains such as wick drains would be added to the capping system, as in Figures 6 and 7. The deeper the deposit of tailings to be dewatered, the more cost-effective capping from a water platform is likely to be. For instance, if a fluid tailings deposit were 20 to 30 m thick, placement from a water platform can be more cost-effective by significant margin, even an order of magnitude less than the customary alternatives, such as placing a cap mechanically over fluid tailings and installing wick drains, or the full cost (including transportation) of implementing centrifuging,
hydrocycloning, thin-lift drying, and other dewatering technologies. In such applications, capping from a water platform has many environmental advantages, including lower CO₂ emissions, less release of gasses from the sediment, maintaining tailings saturation to avoid acid rock drainage issues, and supplying additional useable make-up water to the mine.

9 CONCLUSIONS

Placing caps hydraulically from a water platform offers opportunities to reduce tailings related-risk and closure liabilities, and can prove more practical and more cost-effective than land-based methods, particularly for capping or dewatering very soft to fluid tailings. Table 2 summarizes some of the advantages and disadvantages of the three capping methods discussed in this paper.

<table>
<thead>
<tr>
<th>Capping Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
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<tbody>
<tr>
<td>Earthwork equipment</td>
<td>• Some of the necessary equipment likely available at or near mine site&lt;br&gt;• Limited specialized expertise needed - may be available from mine operations and technical staff&lt;br&gt;• Can be used to place fine-grain capping material&lt;br&gt;• Landform construction can proceed as soon as the cap is trafficable&lt;br&gt;• Requires minimal fixed or set-up costs, can be the most cost effective method for capping relatively small areas.</td>
<td>• Difficult and expensive to implement for very soft to fluid tailings&lt;br&gt;• Uses smaller, lower ground pressure equipment than typical of mining operations</td>
</tr>
<tr>
<td>Hydraulic beaching</td>
<td>• Necessary equipment likely available at or near mine site&lt;br&gt;• Tailings basins operators likely familiar with operational methods&lt;br&gt;• If cell construction or controlled beaching are implemented, may allow some compaction during placement</td>
<td>• Less control over capping material placement, may require more sand to cover the area&lt;br&gt;• Needs water removal, recycle system, and make-up water&lt;br&gt;• Generally not feasible over fluid tailings&lt;br&gt;• Requires aggregate (sand) supply</td>
</tr>
<tr>
<td>Water-based capping</td>
<td>• Very soft tailings can be capped in situ with minimal risk of geotechnical stability problems in the tailings&lt;br&gt;• With careful placement, can cap fluid tailings and very weak soft tailings&lt;br&gt;• Consolidation can be enhanced using wick drains placed from a water platform&lt;br&gt;• No trafficability concerns during construction, can access the full area to be capped, and is operationally flexible&lt;br&gt;• Operations efficient and relatively low cost due to the limited number of personnel necessary, minimal downtime, and efficiency of slurry transport of the cap material</td>
<td>• Specialty personnel and equipment needed to successfully place a cap over fluid (vs. soft) tailings&lt;br&gt;• Techniques and specialty equipment not familiar to mine operators, so need to tap outside expertise for planning, design and implementation&lt;br&gt;• Requires aggregate (sand) supply&lt;br&gt;• Need for management of large volume of water removed after cap placement</td>
</tr>
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REFERENCES


