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Dear Jamie

Tailings Deposition into Open Pit  
Consolidation Modelling and Deposition Concept

1 Introduction

McArthur River Mine (MRM) is planning to utilise the existing pit void, approximately 385 m deep, for long term storage of the tailings and Potential Acid Forming (PAF) waste rock at closure. Tailings are currently stored at the out-of-pit Tailings Storage Facility (TSF) and will be dredged and reprocessed and the resulting tailings slurry would be pumped to the pit void for in-pit disposal. The in-pit deposition will be undertaken over a 10-year period at a production rate of 10.5 Mtpa.

This letter report summarises the results of consolidation analyses undertaken for the in-pit disposal of the tailings under short-term and long-term conditions.

To assist with the analysis, MRM has provided the ultimate pit design, inclusive of the In-Pit Dump (IPD), which is a volume of waste rock that MRM intend to place into the pit during the last 5 to 6 years of mine operation – i.e. before the tailings deposition commences.

In addition to the IPD, MRM has also advised that they intend to co-dispose 7.5MT of PAF waste rock into the pit during the second year of tailings deposition. Waiting until Year 2 – by which point the pit will be partially filled with tailings – will help to reduce the haulage distance for the PAF waste rock.

The rate of rise is anticipated to be very high during initial years (e.g. estimated 96 to 98 metre rise in Year 1) and gradually decreases to 5 to 10 m per year during final years.

2 Objectives

The objectives of the consolidation analyses are to

- to estimate how tailings deposited into the MRM open pit would consolidate under self-weight during and after deposition
- to estimate consolidation water and rate of release into the pond in the pit
- to estimate consolidation time after completion of deposition at closure
- to estimate the dry density of deposited tailings and the storage volumes of tailings during and after deposition under long-term conditions
3 Scope of Work

- Desktop study only, using available information on tailings properties and GHD’s experience in tailings consolidation properties from similar tailings.
- Review KCB groundwater model with regards to the forecast groundwater recharge with time following the cessation of mining activities.
- Review available geotechnical information on the tailings to establish model parameters.
- Model the consolidation of the tailings under self-weight during the deposition cycles and water losses through drainage boundaries using a one dimensional self-weight consolidation program.
- Model consolidation to determine volume of water released to the pit.
- Estimate water loss due to evaporation.
- Estimate the dry density profile of the tailings and the storage capacity of the pit void, including the elevation of the tailings surface is to reach during deposition cycles.
- Make recommendations on next steps to enabling more detailed estimates to be made, including further testing of tailings.

4 Large Deformation Modelling of Tailings Consolidation under Self-Weight

4.1 Tailings Consolidation and Drying
After deposition discharge, tailings slurry with low solids content will bleed due to settling of the tailings particles. Following settling, the tailings will undergo self-weight consolidation and consolidation water will be expelled out of the tailings matrix due to the volume change of the tailings during consolidation. The rate of water coming to the surface from self-weight consolidation is generally greater than evaporation rates due to high moisture content. After initial consolidation, evaporation starts to have an effect on the void ratio when the initial large volume change due to consolidation is diminishing.

4.2 Initial consolidation of tailings – large deformation modelling
During self-weight consolidation, tailings will undergo large deformations because the initial effective stress is low and the void ratio is high in the early stage of development of the tailings matrix. During tailings deposition, the drainage path increases as the thickness of the deposit gradually increases. Therefore, for self-weight consolidation problems, the conventional Terzaghi consolidation theory becomes invalid due to the inherent assumption of infinitesimal strains and fixed drainage paths. Gibson et al. (1967) developed a finite strain consolidation theory for self-weight consolidation and established the governing differential equation. Li et al. (2012) developed an approach to model self-weight consolidation using analytical solutions solved for Gibson consolidation theory. It was proposed to use the following power function to capture high nonlinearity due to initial large volume change at high void ratio for tailings:
\[ e = A \sigma' \]

where:

- \( e \) = void ratio.
- \( \sigma' \) = effective stress.
- \( A, B \) = material constants

The material constants \( A \) and \( B \) can be obtained from fitting the void ratio - log effective stress curve using the above equation.

The modelling approach proposed by Li et al. (2012) was developed specifically for tailings consolidation during deposition at rate of rise and consolidation after deposition. This approach was adopted to model the consolidation behaviour of the MRM tailings during in-pit deposition.

5 Assumptions

For the base case considered, the following key assumptions were made in the analyses.

- The permeability of the rock at the bottom of the pit and around the pit wall is relatively low in comparison to the permeability of the tailings. Therefore, it is reasonably assumed that a one-way drainage to the top will prevail and tailings will consolidate under a one-dimensional condition.
- Tailings and the waste rock will be not comingled.
- The volume change of waste rock is negligible.
- The additional approximately 100m depth of water on top of the subaqueous tailings would have negligible effect on the consolidation of the tailings during post deposition periods, because the tailings are assumed to be essentially saturated throughout the deposit at the end of the deposition in the final year. The 100 m of water would increase the total stress but will not change the effective stress in between tailings particles.
- The potential evaporation rate was assumed to be the same as that used in the O’Kane report (2016). The pan factor due to potential reduced sunlight and wind was not assessed in this study; these could be considered in more detailed future studies.

6 Model Parameters

Two column settling tests were conducted on slurry samples with initial solids content of 55.0% by weight (ATC Williams, 2014) and the settled dry density was estimated to be 1.17 t/m\(^3\) and 1.24 t/m\(^3\) respectively. The specific gravity of the tailings is approximately 3.2. The consolidation tests have been carried out by GHD (2016) and University of Queensland (2016) on tailings samples recovered from the TSF. Figure 1 summarises the results of the previous consolidation tests. Sample 2 was taken from the tailings beach with coarser tailings and Sample 5 was taken near the decant pond with finer tailings. Sample 1 represents an average sample with respect to particle size distribution. Using Eq. 1 to match
the results of the settling test and consolidation tests, the power function constants A and B were estimated to be 1.5 and -1.2, respectively.

A coefficient of consolidation of 2.0 m/month was selected based on the average value of the coefficients of consolidation measured in the laboratories as shown in Figure 2.

**Figure 1 Results of Consolidation Tests and Selected Consolidation Curve for in-pit Tailings**
Figure 2 Coefficient of Consolidation

Sample (2015) at depth 6.65m
UQ Density 1.7t/m³
UQ Density 1.9t/m³
Average
7 Modelling Results

7.1 Consolidation During Deposition
The initial consolidation analyses were carried out to predict the elevation of the tailings surface at the end of each year based on the production of the tailings for in-pit disposal. The tailings surface level was determined through iterative analyses based on the average dry density of the tailings deposit and the estimated volume of the tailings at each modelling period. Table 1 summarises the results of the predicted tailings surface levels and the average dry density for each year.

Table 1 Predicted Dry Density Widths of sections to calculate seepage

<table>
<thead>
<tr>
<th>Year</th>
<th>Stored Dry Mass (tonne)</th>
<th>Dry Density $\gamma_d$ (t/m$^3$)</th>
<th>Height from Base* (m)</th>
<th>Elevation MGA94* (m)</th>
<th>Rate of Rise* (m/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year 1</td>
<td>10,500,000</td>
<td>1.387</td>
<td>96.0</td>
<td>-289.0</td>
<td>96.0</td>
</tr>
<tr>
<td>Year 2</td>
<td>21,000,000</td>
<td>1.399</td>
<td>136.0</td>
<td>-248.0</td>
<td>41.0</td>
</tr>
<tr>
<td>Year 3</td>
<td>31,500,000</td>
<td>1.415</td>
<td>154.0</td>
<td>-230.0</td>
<td>18.0</td>
</tr>
<tr>
<td>Year 4</td>
<td>42,000,000</td>
<td>1.427</td>
<td>169.0</td>
<td>-214.0</td>
<td>16.0</td>
</tr>
<tr>
<td>Year 5</td>
<td>52,500,000</td>
<td>1.420</td>
<td>183.0</td>
<td>-200.0</td>
<td>14.0</td>
</tr>
<tr>
<td>Year 6</td>
<td>63,000,000</td>
<td>1.445</td>
<td>194.0</td>
<td>-188.0</td>
<td>12.0</td>
</tr>
<tr>
<td>Year 7</td>
<td>73,500,000</td>
<td>1.452</td>
<td>204.0</td>
<td>-177.0</td>
<td>11.0</td>
</tr>
<tr>
<td>Year 8</td>
<td>84,000,000</td>
<td>1.459</td>
<td>214.0</td>
<td>-167.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Year 9</td>
<td>94,500,000</td>
<td>1.464</td>
<td>223.0</td>
<td>-157.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Year 10</td>
<td>105,000,000</td>
<td>1.473</td>
<td>227.0</td>
<td>-152.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>

*Note: The levels and heights shown here are based on the pit storage spreadsheet provided by MRM on 16 Sep 2016 and were the basis of the consolidation modelling. In the attached drawings SK001 to SK005, GHD has also calculated tailings fill volumes and levels based upon the pit CAD model provided by MRM on 06 Sep 2016. There are some minor differences between the year-to-year levels shown in the table above and the attached drawings (on average less than 0.5m per year), which are considered to be negligible for the current study.

Figure 3 shows the predicted density profile at the end of each operating year. Due to one-way drainage condition and the relatively high rate of rise of the tailing surface, the tailings in the upper part of the pit would not experience significant consolidation during deposition and the dry density would be constant at the initial dry density after settling. The tailings in the lower part of the pit will consolidate during
deposition and the density increases with depth. The degree of consolidation with respect to settlement ranges from 9.9% at the end of the first year to 33.0% at the end of the last year.

**Figure 3 Dry Density Profiles of the Tailings During Deposition**
7.2 Consolidation Water

Table 2 shows the accumulative consolidation water released to the surface, estimated flow rate and average flux during the 10 years of the operating period. Figure 4 shows the estimated accumulative consolidation water, increasing from approximately 0.93 Mm$^3$ in Year 1 to 13.07 Mm$^3$ in Year 10. The estimated annual average flux from the underlying tailings to the tailings surface ranges from 12.4 mm/day/m$^2$ in Year 1 to 3.7 mm/day/m$^2$ in Year 10.

The average annual potential evaporation rate is approximately 1990 mm/year corresponding to 5.5 mm/day (O’Kane Consultants, 2016). Based on the estimated release rate of consolidation water to the pit, the tailings are anticipated to be essentially saturated from Year 1 to Year 9 under average weather conditions. In other words, the rate of tailings water loss due to the evaporation would be at a rate of 5.5 mm/day/m$^2$ under the average weather conditions. The results of the consolidation analysis suggest that the subaerial deposition would not provide significant advantages with respect to water losses and volume change of the tailings under the average weather conditions.

Table 2 Estimated Consolidation Water, Flow Rate and Average Flux during Deposition

<table>
<thead>
<tr>
<th>Year</th>
<th>Tailings (tonne)</th>
<th>Accumulative Consolidation Water (m$^3$)</th>
<th>Average Flow Rate (m$^3$/year)</th>
<th>Surface Area (m$^2$)</th>
<th>Average Flux (mm/day/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year 1</td>
<td>10,500,000</td>
<td>933,578</td>
<td>933,578</td>
<td>205,966</td>
<td>12.4</td>
</tr>
<tr>
<td>Year 2</td>
<td>21,000,000</td>
<td>1,994,680</td>
<td>1,061,102</td>
<td>373,075</td>
<td>7.8</td>
</tr>
<tr>
<td>Year 3</td>
<td>31,500,000</td>
<td>3,244,492</td>
<td>1,249,813</td>
<td>446,472</td>
<td>7.7</td>
</tr>
<tr>
<td>Year 4</td>
<td>42,000,000</td>
<td>4,575,578</td>
<td>1,331,086</td>
<td>509,506</td>
<td>7.2</td>
</tr>
<tr>
<td>Year 5</td>
<td>52,500,000</td>
<td>5,538,522</td>
<td>962,945</td>
<td>573,851</td>
<td>4.6</td>
</tr>
<tr>
<td>Year 6</td>
<td>63,000,000</td>
<td>7,415,108</td>
<td>1,876,585</td>
<td>640,036</td>
<td>8.0</td>
</tr>
<tr>
<td>Year 7</td>
<td>73,500,000</td>
<td>8,894,673</td>
<td>1,479,565</td>
<td>676,049</td>
<td>6.0</td>
</tr>
<tr>
<td>Year 8</td>
<td>84,000,000</td>
<td>10,442,897</td>
<td>1,548,223</td>
<td>736,427</td>
<td>5.8</td>
</tr>
<tr>
<td>Year 9</td>
<td>94,500,000</td>
<td>11,987,700</td>
<td>1,544,804</td>
<td>768,886</td>
<td>5.5</td>
</tr>
<tr>
<td>Year 10</td>
<td>100,000,000</td>
<td>13,066,624</td>
<td>1,078,924</td>
<td>805,614</td>
<td>3.7</td>
</tr>
</tbody>
</table>
After deposition, the tailings will continue to consolidate under self-weight and water in the tailings matrix will be expelled and release to the tailings surface due to volume change and decrease in void ratio. Consolidation settlement will also develop and result in a lowering tailings surface with time until consolidation is completed. The degree of the consolidation is estimated based on the settlement. Figure 5 shows the estimated maximum settlement at the centre of the pit (i.e. the deepest location) versus time. It is estimated that the tailings will reach 35.0%, 43.0%, 90.0% and 98% consolidation after 1 year, 10 years, 100 years and 300 years respectively, during the post deposition periods. The maximum consolidation settlement would be 54.0 m at the centre of the pit. However, the average settlement could be less than 27.0 m due to the three dimensional effect. Figure 8 shows the dry density profiles at Year 20, Year 100, Year 300 and at the end of consolidation. The final average dry density is estimated to be 1.93 t/m$^3$. 

7.3 Consolidation after Deposition

Figure 4 Estimated Consolidation Water to be Released to the Pond
The estimated accumulative consolidation water after the deposition is shown in Figure 6. The volume of the consolidation water is estimated to decrease from 220,900 m$^3$ in the initial year (Year 11) to less than 4,000 m$^3$ in Year 300. The estimated daily flow rate is shown in Figure 7.

**Figure 5 Settlement vs. Time After Deposition**

![Figure 5 Settlement vs. Time After Deposition](image)

**Figure 6 Consolidation Water to Be Released to the Pond During Post Deposition Periods**

![Figure 6 Consolidation Water to Be Released to the Pond During Post Deposition Periods](image)
Figure 7 Flow Rate of Consolidation Water During Post Deposition Periods

Flow rate (m³/day)

Time after Deposition (year)
Figure 8 Estimated Dry Density Profiles During Post Deposition Periods
8 Water Balance Estimates

In addition to the estimates of consolidation water volumes provided above in Section 7, we have also estimated the overall volume of free water that could be generated by the tailings in-pit deposition operation, and the volume of make-up water that could be required each year at the TSF to continue slurrying of the tailings with water monitors as described in the draft Retreat Concept report (MRM, 2016).

The water balance estimates take into consideration the following elements:

- Tailings density and moisture content characteristics as summarised in Table 3 below.
- Bleed water recovered from the initial settlement of the tailings once deposited into the pit (i.e. the differential water content between Stages 2 and 3 in Table 3 below).
- Free water generated from consolidation of the tailings (i.e. consolidation water, as calculated in Section 7 above).
- Annual average evaporation from the surface area of the tailings (2,735 mm per annum).
- Annual average rainfall over the plan area of the pit (805 mm per annum over an area of 2.555Mm²). A run-off coefficient of 1 has been selected for rainfall, and a sensitivity analysis was conducted by considering a range of annual rainfalls from the 10th percentile (i.e. dry) year to the 90th percentile (i.e. wet year).

As advised by KCB (ref email dated 20th Sep 2016, titled “MRM In-Pit Tailings Consolidation Works - notes from kick off meeting - groundwater inputs”), groundwater and potential inflows from McArthur River, were not considered in this water balance estimate, on the basis that:

- There will be no river flow entering the pit during tailings/waste rock placement.
- Groundwater will continue to be managed through the dewatering system and will not enter the pit.

<table>
<thead>
<tr>
<th>Property</th>
<th>Stage 1 Tailings in TSF</th>
<th>Stage 2 Tailings Slurry Piped from TSF to Pit</th>
<th>Stage 3 Tailings in Pit Following Initial Settlement</th>
<th>Stage 4 Tailings in Pit After 10 Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>% solids by weight</td>
<td>82%</td>
<td>45%</td>
<td>66.1%</td>
<td>72.2%</td>
</tr>
<tr>
<td>% water by weight</td>
<td>18%</td>
<td>55%</td>
<td>33.9%</td>
<td>27.8%</td>
</tr>
<tr>
<td>% solids by volume</td>
<td>59%</td>
<td>21%</td>
<td>38.1%</td>
<td>45.2%</td>
</tr>
<tr>
<td>% voids by volume</td>
<td>41%</td>
<td>79%</td>
<td>61.9%</td>
<td>54.8%</td>
</tr>
<tr>
<td>Dry density [t/m3]</td>
<td>1.85</td>
<td>0.65</td>
<td>1.21</td>
<td>1.43</td>
</tr>
</tbody>
</table>
Table 4 provides a summary of the water balance calculations undertaken and indicates that make up water in the range of 0.62 to 2.11 Mm³ would be required at the TSF in order to slurry the tailings for the case of average annual rainfall in each year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Water required at TSF to slurry tailings [m³]</th>
<th>Bleed water from initial settlement [m³]</th>
<th>Consolidation water [m³]</th>
<th>Evaporation from tailings beach area [m³]</th>
<th>Average rainfall inflow from pit catchment</th>
<th>Make Up Water Required at TSF (Mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10,478,170</td>
<td>7,440,153</td>
<td>933,578</td>
<td>-563,317</td>
<td>2,049,216</td>
<td>0.62</td>
</tr>
<tr>
<td>2</td>
<td>10,478,170</td>
<td>7,440,153</td>
<td>1,061,102</td>
<td>-1,020,360</td>
<td>2,049,216</td>
<td>0.95</td>
</tr>
<tr>
<td>3</td>
<td>10,478,170</td>
<td>7,440,153</td>
<td>1,249,813</td>
<td>-1,221,101</td>
<td>2,049,216</td>
<td>0.96</td>
</tr>
<tr>
<td>4</td>
<td>10,478,170</td>
<td>7,440,153</td>
<td>1,331,086</td>
<td>-1,393,499</td>
<td>2,049,216</td>
<td>1.05</td>
</tr>
<tr>
<td>5</td>
<td>10,478,170</td>
<td>7,440,153</td>
<td>962,945</td>
<td>-1,569,482</td>
<td>2,049,216</td>
<td>1.60</td>
</tr>
<tr>
<td>6</td>
<td>10,478,170</td>
<td>7,440,153</td>
<td>1,876,585</td>
<td>-1,750,498</td>
<td>2,049,216</td>
<td>0.86</td>
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<tr>
<td>7</td>
<td>10,478,170</td>
<td>7,440,153</td>
<td>1,479,565</td>
<td>-1,848,994</td>
<td>2,049,216</td>
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<td>8</td>
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<td>7,440,153</td>
<td>1,548,223</td>
<td>-2,014,128</td>
<td>2,049,216</td>
<td>1.45</td>
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<td>7,440,153</td>
<td>1,544,804</td>
<td>-2,102,903</td>
<td>2,049,216</td>
<td>1.55</td>
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<tr>
<td>10</td>
<td>10,478,170</td>
<td>7,440,153</td>
<td>1,078,924</td>
<td>-2,203,354</td>
<td>2,049,216</td>
<td>2.11</td>
</tr>
</tbody>
</table>
In the case of 10\textsuperscript{th} percentile rainfall occurring each year, an additional 0.9Mm\textsuperscript{3} of make-up water would be required each year.

In the case of 90\textsuperscript{th} percentile rainfall occurring each year we estimate that 0.98Mm\textsuperscript{3} less make-up water would be required each year, such that there would be a surplus of water in Years 1, 2, 3 and 6.

9 Tailings Deposition Concept

The attached drawings SK001 to SK005 provide an indication of the filling of the pit over the 10 years. Key aspects of the deposition concept include:

- Tailings discharge pipe installed along the Western Ramp, and then down the western pit wall which has a gradient of approximately 20°. Access to the discharge point would be required so that it could be regularly adjusted – to allow for the increasing tailings beach elevation – and realigned northwards / southwards to maximise the efficiency of the tailings deposition into the pit.
- Tailings beach of a similar gradient (1V:150H) to that at the TSF has been estimated for this study.
- A decant pond at the eastern side of the pit, to enable access to the pond via the main ramp for installation and maintenance of pump(s) and associated infrastructure.
- Construction of the 7.5 MT PAF waste rock cell in Year 2, based on its height being the same as the depth of tailings deposited in Year 2. We have attempted to maximise the founding of the PAF waste rockfill on rock (i.e. the IPD and the pit), however the drawings indicate that a portion of the rockfill would be founded on tailings. The feasibility of this will require further analysis and consideration because the tailings may not have sufficient strength to support such a rapid development of the waste rockfill without careful design, planning and implementation.

10 Recommendations

It should be noted that consolidation of the tailings under self-weight will depend on the consolidation characteristics of the tailings under different stress conditions encompassing a stress range from very low effective stress after settling to very high effect stress at the bottom of the pit. The following recommendations are provided for the further study of the project.

- Column settling tests should be carried out at the target solids content.
- Slurry consolidation tests should be carried out on the representative tailings samples to characterise the consolidation properties of the tailings at different initial solids content.
- It is recommended to carry out the slurry consolidation tests in connections of permeability tests at different stress levels.
- More detailed analyses should be undertaken with consolidation of three dimensional effect of the pit geometries and the effect of the waste rock on the consolidation of the tailings.
- The evaporative drying modelling of the tailings and drying tests should be carried out only to investigate the effects of volume change during desiccation if a subaerial deposition is to be adopted and the tailings are anticipated to be desiccated during dry seasons.
Options for co-disposal of the 7.5MT PAF rockfill with the tailings in Year 2 should be further considered. From a geotechnical perspective, it would be preferable to found the rockfill on rock. In this regard, the possibility of spreading the rockfill disposal over a longer time period so that it could have a greater height, and lesser footprint area could be considered. If the rockfill is to be founded on tailings, further analysis and modelling should be undertaken to determine a suitable way for undertaking this safely, in order to maintain stability of the placed rockfill and so as to maintain the decant water quality.

11 References


MRM, 2016. MRM Tailings Retreatment Project Concept Study, 04 April 2016 Version 1 (Draft)

O’Kane Consultants, 2016, McArthur River Mine – Initial Consolidation Modelling for In-Pit Tailings; Fatal Flaw Analysis for Pit Water Quality. 29 May 2016.

Kind Regards
GHD Pty Ltd

Allen Li & Matthew Daley