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Appendix P – Revised Tailings Consolidation Report

5 December 2017

Jamie Hacker
McArthur River Mining
PO Box 36821
Winnellie NT 0821

Our ref:
G:\32\1747605\WP\65221
Addendum 2017-12-04.docx
Your ref:

Dear Jamie

Addendum to GHD Report - Tailings Deposition Open Pit Consolidation Modelling and Deposition Concept – Sensitivity Analysis

1 Introduction

McArthur River Mining (MRM) engaged GHD to conduct a sensitivity assessment of the tailings consolidation for the proposed in-pit disposal. GHD (2016) conducted a preliminary consolidation analysis to estimate the potential water release from the tailings consolidation during deposition and closure periods based on the results of the oedometer tests. Subsequently, a settling and self-weight consolidation test using a test column and a slurry consolidation test using a Rowe cell were undertaken to characterise the consolidation characteristics of the slurried tailings. A sensitivity study was carried out for a range of values adopted for the coefficient of consolidation of the tailings.

This report addendum presents the results laboratory column and the Rowe cell tests and the results of the sensitivity analysis, and should be read in conjunction with GHD (2016)

2 Settling and Self-Weight Consolidation Column Test

Tailings column settling and self-weight consolidation testing was carried out by the GHD soil laboratory using a 1-m high and 190-mm diameter column. The test was conducted under undrained conditions with the initial solids content of 45 % by weight, which is the targeted solids content for the in-pit storage. Figures 1 and 2 show the results of the column test, which are summarised as below:

- Time to reach 100% consolidation T_{100}: 4.2 days
- Volume change after consolidation: 52%
- Dry density after consolidation: 1.24%

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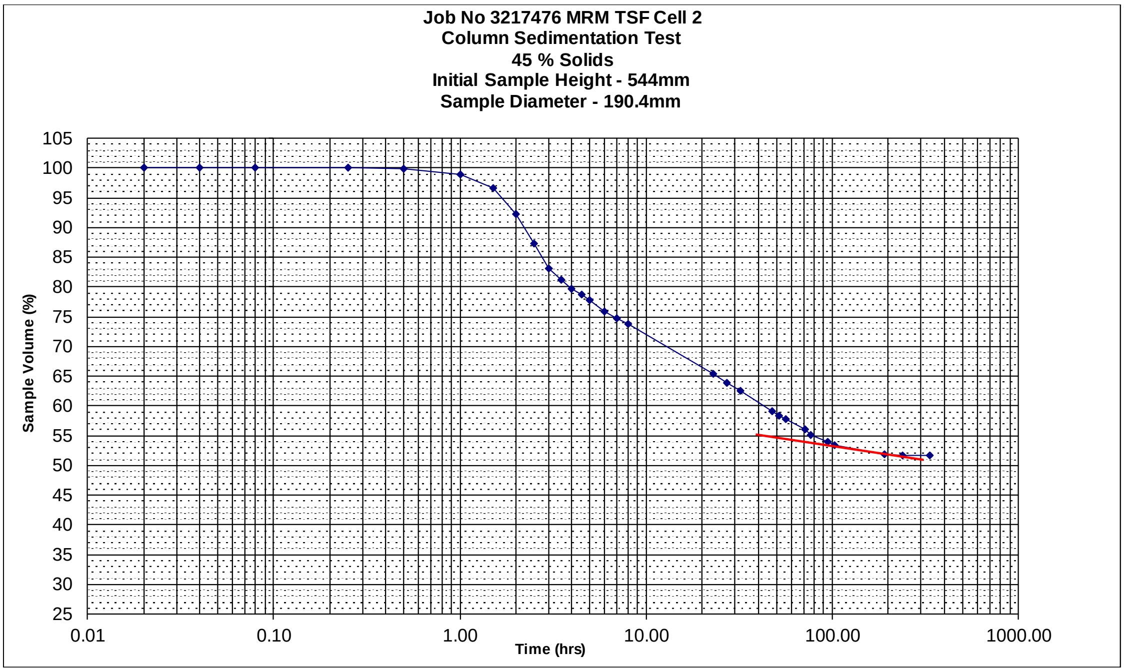

Figure 1 Column Self-Weight Consolidation Test – Volume Change vs. Time

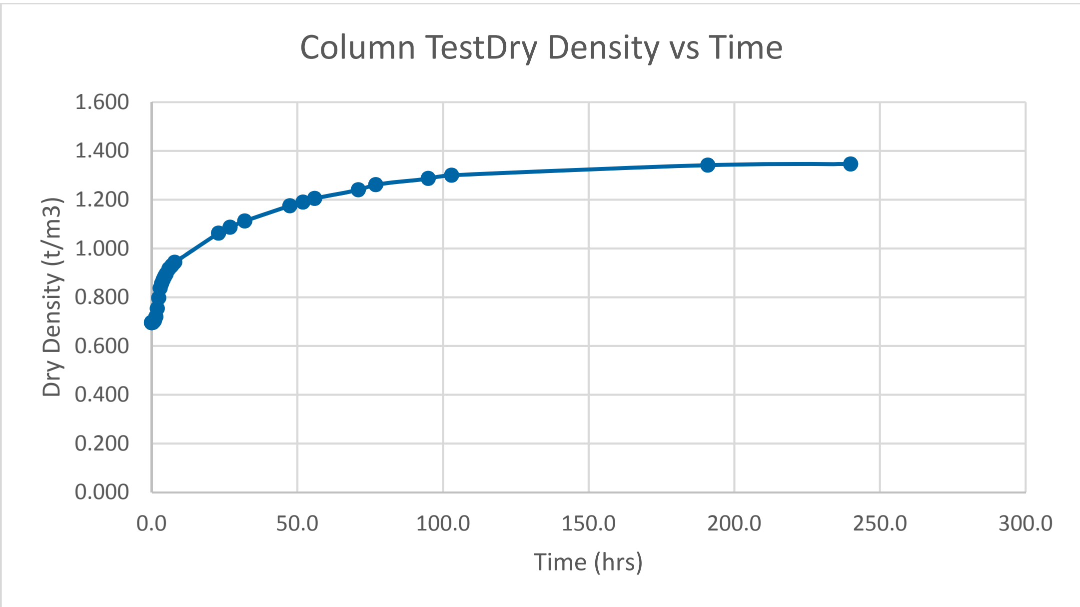

Figure 2 Column Settling and Self-Weight Consolidation Test – Dry Density vs. Time

During self-weight consolidation, tailings will undergo large deformations because the initial effective stress is low and void ratio is high in the early stage of development of tailings matrix. 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. Due to the nonlinearity of the compressibility of the tailings, it was proposed to use the following power function to capture the initial large volume change at high void ratio for tailings:

$$e = A\sigma'^{B}$$

where:

e = void ratio.

σ' = effective stress.

A, B = material constants

The material constants A and B can be obtained from fitting the void ratio - logarithm 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.

Figure 3 shows a comparison of the measured settlement curve and the predicted settlement curve using the adopted compressibility function and back-calculated coefficient of consolidation. The following key properties were inferred from the column test:

- Coefficient of consolidation at the low range of the vertical effective stress up to 1.7 kPa: 0.07 m^2/month
- Compressibility parameters A: 1.8 (in comparison to 1.5 based on previous tests (GHD, 2016))
- Compressibility parameter B: -0.488 (in comparison to -0.12 based on previous tests (GHD, 2016))

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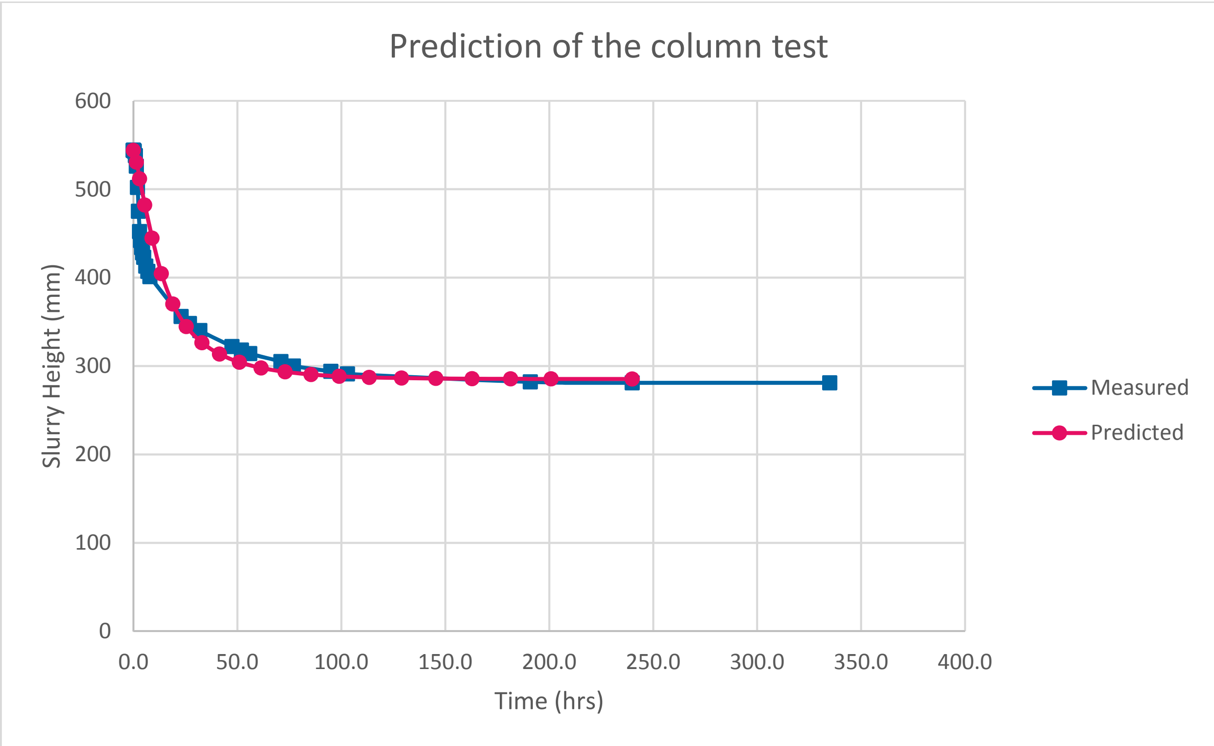

Figure 3 Prediction of the Settlement for the Column Test

As is shown in the column test, the initial consolidation immediately after deposition of the slurry tailings would only take approximately 4 days to complete. The long term consolidation of the tailings would mainly depend upon the consolidation characteristics of the tailings in the higher stress range.

3 Slurry Consolidation

Slurry consolidation tests were undertaken by Fugro using a Rowe cell consolidometer. The slurry sample was prepared with an initial dry density approximately the same as the final dry density of the tailings after self-weight consolidation. Constant head permeability tests were performed at different consolidation pressures.

Figure 4 shows the consolidation curve of the tailings determined from the Rowe cell consolidation tests and Table 1 provides a summary of the test results. The details of the tests are included in Attachment 1.

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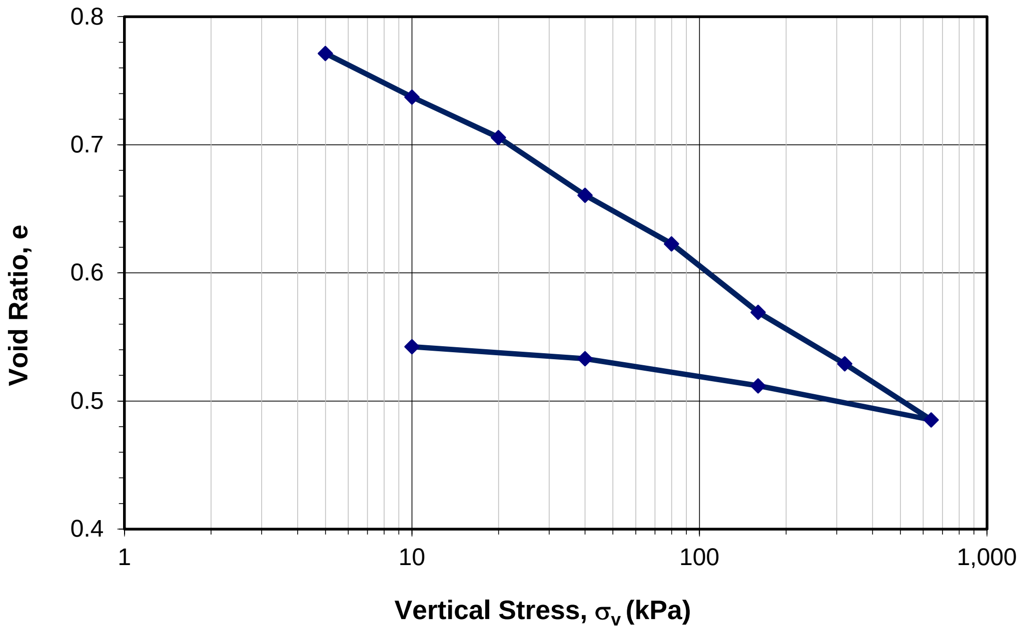

Figure 4 Consolidation Curve and Rebounded Curve in the e-logσ_v' Space

Table 1 Summary of the results of the Consolidation and Permeability Tests.

Stage		s_v	e	c_v	m_v	k	
						Calculated	Measured
		kPa		m²/year	m²/kN	m/sec	m/sec
Seating	0	2.5	0.793	-	-	-	-
Loading	1	5	0.771	-	-	-	-
	2	10	0.737	17.9	3.84E-03	2.13E-08	-
	3	20	0.706	31.2	1.82E-03	1.77E-08	1.47E-08
	4	40	0.661	35.2	1.32E-03	1.44E-08	1.25E-08
	5	80	0.623	59.6	5.71E-04	1.06E-08	9.81E-09
	6	160	0.569	64.4	4.12E-04	8.26E-09	7.77E-09
	7	320	0.529	110.8	1.60E-04	5.52E-09	6.58E-09
	8	640	0.485	117.3	8.94E-05	3.26E-09	4.88E-09
Unloading	9	160	0.512	-	-	-	-
	10	40	0.533	-	-	-	-
	11	10	0.542	-	-	-	

The Rowe Cell Consolidation Test results from Fugro are attached at the end of this report.

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4 Sensitivity Analysis

4.1 Coefficient of Consolidation

Consolidation of a soil is governed by the coefficient of consolidation (c_v) of the soil and the length of the drainage path. The coefficient of consolidation is proportional to the permeability (k) of the soil and inversely proportional to the compressibility (m_v) of the soil. Since the permeability decreases with consolidation and the compressibility also decreases with consolidation, the combined effects on the coefficient of consolidation is reduced. The analytical solution proposed by Li et al. (2012) adopts the coefficient of consolidation in the analysis.

During Rowe cell testing of the MRM tailings, the measured permeability ranged from 1.47×10^{-8} m/s to 4.88×10^{-9} m/s (i.e. an approximately 3 times reduction) and the measured compressibility ranged from 3.84×10^{-3} kPa^{-1} to 8.94×10^{-3} kPa^{-1} (i.e. an approximately 43 times reduction), however, the coefficient of consolidation ranged from 17.9 m m^2/year to 117.3 m^2/year (an approximately 6.6 times increase) due to the combined effects of the permeability and the compressibility.

Figure 5 shows the coefficients of consolidation measured from the Rowe cell and oedometer consolidation tests on the MRM tailings. As is shown in Figure 5, c_v ranged from 0.6 m^2/month to 9.8 m^2/month. Based on the test data, the sensitivity analysis was undertaken using c_v values of 1.0, 2.0, 6.0 and 9.8 m^2/month.

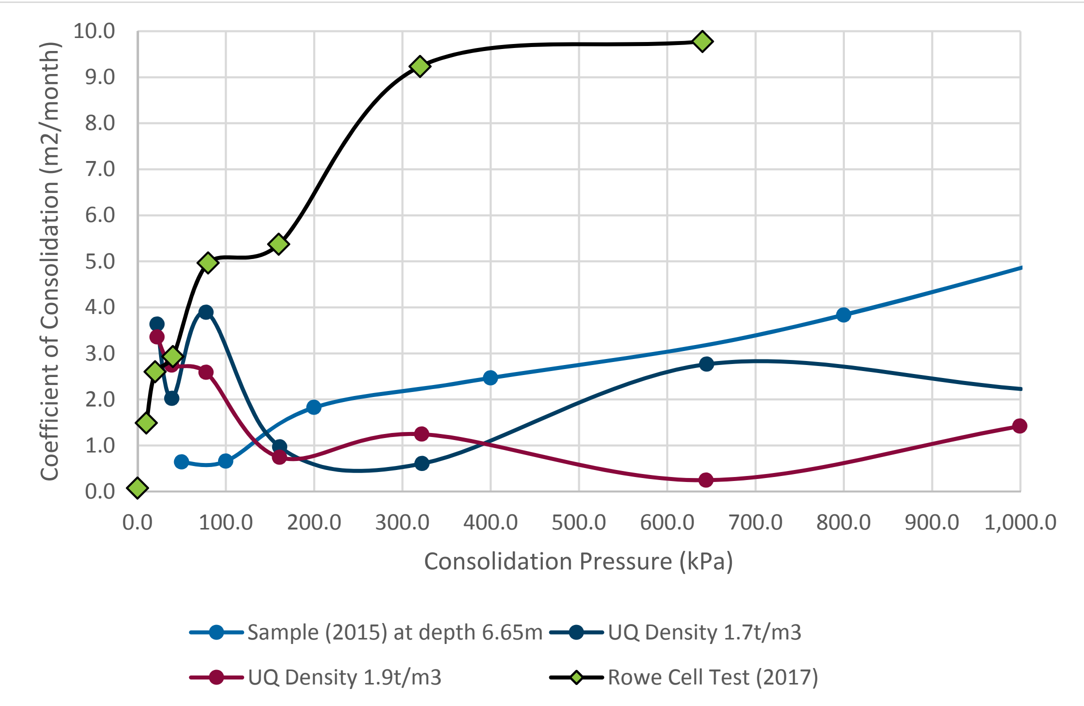

Figure 5 Variation of the Coefficient of Consolidation with Consolidation Pressure

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Figure 6 presents the results of the consolidation tests carried out from previous studies and the current study. The dashed consolidation curve was selected in the original analysis (GHD, 2016). In the sensitivity analysis, the following parameters were used:

- Case 1: c_v = 1.0 m^2/month, compressibility model parameters A = 1.5, B = -0.12 (dashed line in Figure 6)
- Case 2 (i.e. the original analysis): c_v = 2.0 m^2/month, compressibility model parameters A = 1.5, B = -0.12 (dashed line in Figure 6)
- Case 3: c_v = 6.0 m^2/month, compressibility model parameters A = 1.5, B = -0.12 (dashed line in Figure 6)
- Case 4: c_v = 9.8 m^2/month, compressibility model parameters A = 1.0, B = -0.11 (solid line in Figure 6 based on the Rowe cell test)

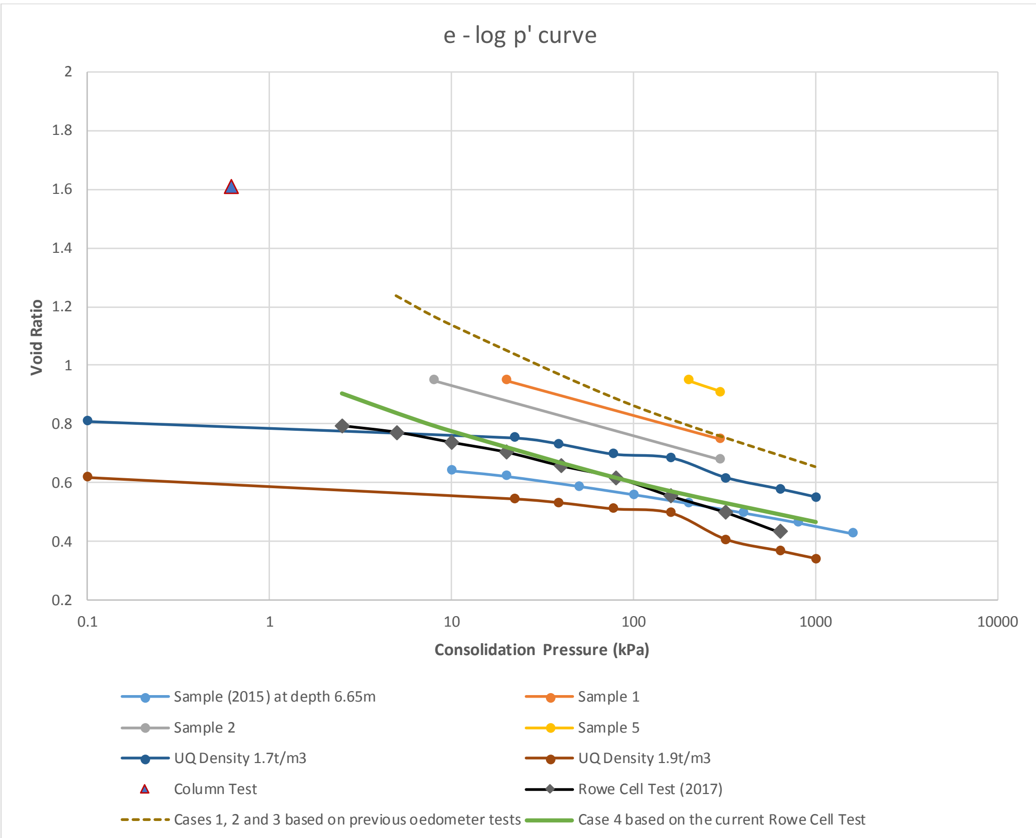

Figure 6 Results of Consolidation Tests and Selected Consolidation Curves for the In-Pit Tailings Deposition

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4.2 Results of the Sensitivity Analysis

In the sensitivity analyses, the consolidation of tailing analysis was carried out for the operating years 1 to 10 during in-pit deposition and the post closure periods. The dry density of the tailings was calculated in each analysis and the volume of the tailings was determined to estimate the depth of the tailings surface at the end of the each operation year. The volume of water released during deposition was estimated based on the change in void ratio. During the post closure periods, the tailings will continue to consolidate with time and the settlement curve was determined to estimate the degree of consolidation at different time after the deposition.

Tables 2, 3, 4 and 5 summarise the estimated bleed water and consolidation water together with the locked-in water in the tailings matrix. Figures 7, 8, 9 and 10 show the time dependent water release due to consolidation during the closure periods.

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Table 2 Results of Case 1 with cv = 1.0 m^2/month

	Tailings	Total water in tailings slurry	Water retained in tailings matrix after initial settling	Bleed Water (water released during initial settling)	Locked-in Water	Cumulative Consolidation Water (water released during consolidation)
	(tonne)	(m^3)	(m^3)	(m^3)	(m^3)	(m^3)
Year 1	10,500,000	12,833,333	5,241,468	7,591,866	4,527,461	714,007
Year 2	21,000,000	25,666,667	10,482,936	15,183,731	8,806,518	1,676,418
Year 3	31,500,000	38,500,000	15,724,403	22,775,597	13,205,580	2,518,824
Year 4	42,000,000	51,333,333	20,965,871	30,367,462	17,427,674	3,538,197
Year 5	52,500,000	64,166,667	26,207,339	37,959,328	20,668,817	5,538,522
Year 6	63,000,000	77,000,000	31,448,807	45,551,193	26,028,361	5,420,446
Year 7	73,500,000	89,833,333	36,690,275	53,143,059	29,878,074	6,812,201
Year 8	84,000,000	102,666,667	41,931,742	60,734,924	34,012,027	7,919,716
Year 9	94,500,000	115,500,000	47,173,210	68,326,790	35,185,510	11,987,700
Year 10	100,000,000	122,222,222	49,918,741	72,303,481	39,667,590	10,251,151
Final	100,000,000	122,222,222	49,918,741	72,303,481	20,946,902	28,971,839

Table 3 Results of Case 2 with cv = 2.0 m^2/month

	Tailings	Total water in tailings slurry	Water retained in tailings matrix after initial settling	Bleed Water (water released during initial settling)	Locked-in Water	Cumulative Consolidation Water (water released during consolidation)
	(tonne)	(m^3)	(m^3)	(m^3)	(m^3)	(m^3)
Year 1	10,500,000	12,833,333	5,241,468	7,591,866	4,307,890	933,578
Year 2	21,000,000	25,666,667	10,482,936	15,183,731	8,488,256	1,994,680
Year 3	31,500,000	38,500,000	15,724,403	22,775,597	12,479,911	3,244,492
Year 4	42,000,000	51,333,333	20,965,871	30,367,462	16,390,293	4,575,578
Year 5	52,500,000	64,166,667	26,207,339	37,959,328	20,668,817	5,538,522
Year 6	63,000,000	77,000,000	31,448,807	45,551,193	24,033,699	7,415,108
Year 7	73,500,000	89,833,333	36,690,275	53,143,059	27,795,601	8,894,673
Year 8	84,000,000	102,666,667	41,931,742	60,734,924	31,488,846	10,442,897
Year 9	94,500,000	115,500,000	47,173,210	68,326,790	35,185,510	11,987,700
Year 10	100,000,000	122,222,222	49,918,741	72,303,481	36,852,117	13,066,624
Final	100,000,000	122,222,222	49,918,741	72,303,481	20,900,835	29,017,906

Table 4 Results of Case 3 with cv = 6.0 m^2/month

	Tailings	Total water in tailings slurry	Water retained in tailings matrix after initial settling	Bleed Water (water released during initial settling)	Locked-in Water	Cumulative Consolidation Water (water released during consolidation)
	(tonne)	(m^3)	(m^3)	(m^3)	(m^3)	(m^3)
Year 1	10,500,000	12,833,333	5,241,468	7,591,866	3,795,906	1,445,562
Year 2	21,000,000	25,666,667	10,482,936	15,183,731	7,432,501	3,050,434
Year 3	31,500,000	38,500,000	15,724,403	22,775,597	10,793,675	4,930,729
Year 4	42,000,000	51,333,333	20,965,871	30,367,462	14,055,667	6,910,204
Year 5	52,500,000	64,166,667	26,207,339	37,959,328	17,789,330	8,418,009
Year 6	63,000,000	77,000,000	31,448,807	45,551,193	20,388,380	11,060,427
Year 7	73,500,000	89,833,333	36,690,275	53,143,059	23,493,075	13,197,200
Year 8	84,000,000	102,666,667	41,931,742	60,734,924	26,583,795	15,347,948
Year 9	94,500,000	115,500,000	47,173,210	68,326,790	29,574,875	17,598,335
Year 10	100,000,000	122,222,222	49,918,741	72,303,481	30,866,022	19,052,719
Final	100,000,000	122,222,222	49,918,741	72,303,481	20,731,391	29,187,350

Table 5 Results of Case 4 with cv = 9.8 m^2/month

	Tailings	Total water in tailings slurry	Water retained in tailings matrix after initial settling	Bleed Water (water released during initial settling)	Locked-in Water	Cumulative Consolidation Water (water released during consolidation)
	(tonne)	(m3)	(m3)	(m3)	(m3)	(m3)
Year 1	10,500,000	12,833,333	5,241,468	7,591,866	2,081,298	3,160,170
Year 2	21,000,000	25,666,667	10,482,936	15,183,731	4,051,276	6,431,659
Year 3	31,500,000	38,500,000	15,724,403	22,775,597	5,841,156	9,883,248
Year 4	42,000,000	51,333,333	20,965,871	30,367,462	7,566,056	13,399,815
Year 5	52,500,000	64,166,667	26,207,339	37,959,328	9,586,319	16,621,020
Year 6	63,000,000	77,000,000	31,448,807	45,551,193	10,931,574	20,517,232
Year 7	73,500,000	89,833,333	36,690,275	53,143,059	12,575,996	24,114,279
Year 8	84,000,000	102,666,667	41,931,742	60,734,924	14,259,044	27,672,698
Year 9	94,500,000	115,500,000	47,173,210	68,326,790	15,192,095	31,981,116
Year 10	100,000,000	122,222,222	49,918,741	72,303,481	16,440,725	33,478,016
Final	100,000,000	122,222,222	49,918,741	72,303,481	11,275,207	38,643,534

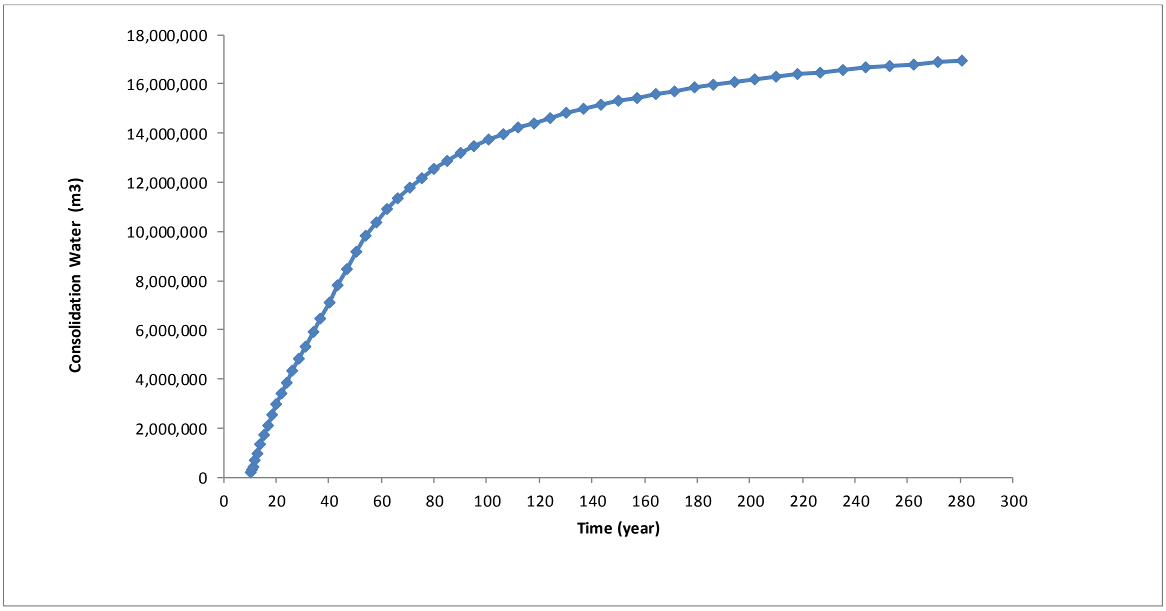


Figure 7 Case 1 Consolidation Water to Be Released to the Pond during Post Deposition Periods

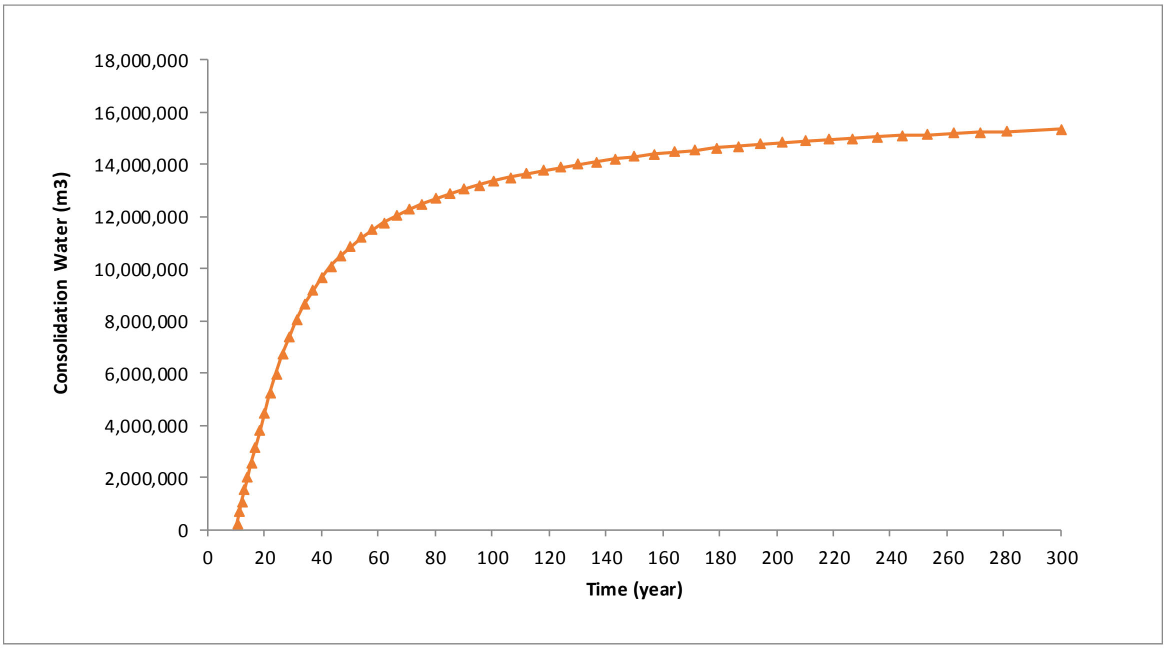


Figure 8 Case 2 Consolidation Water to Be Released to the Pond during Post Deposition Periods

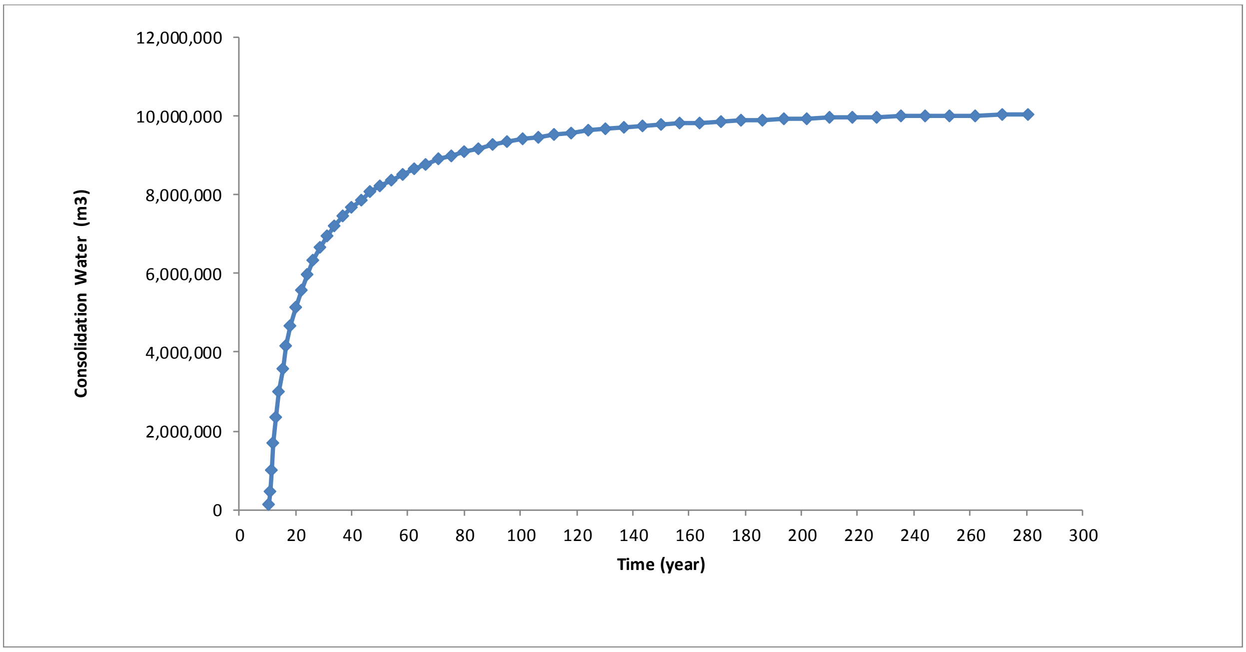


Figure 9 Case 3 Consolidation Water to Be Released to the Pond during Post Deposition Periods

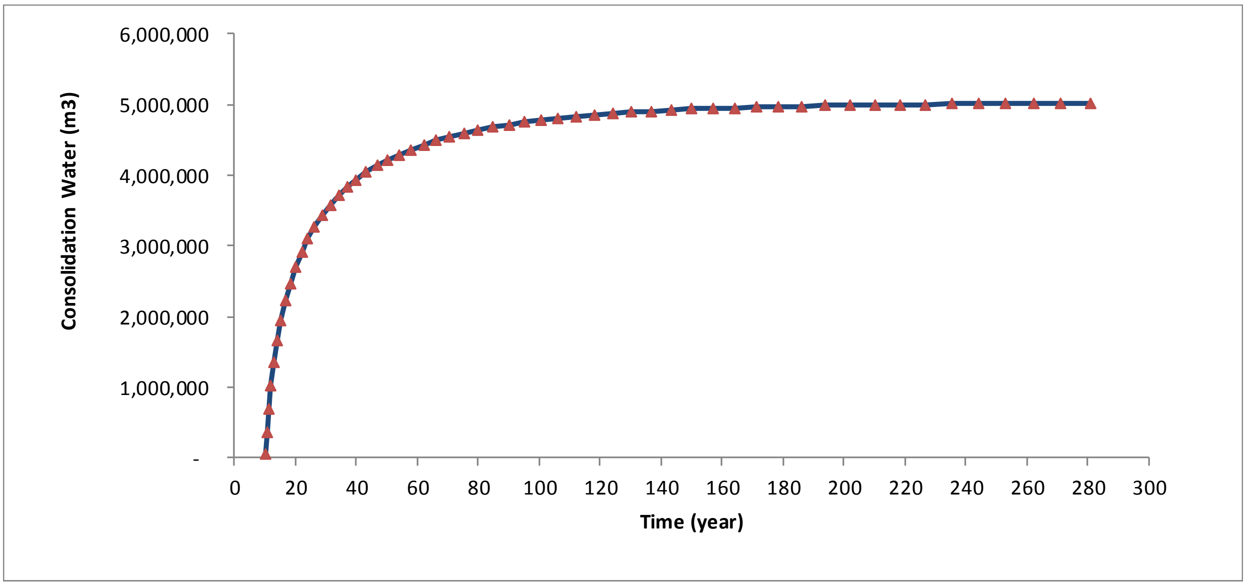


Figure 10 Case 4 Consolidation Water to Be Released to the Pond during Post Deposition Periods

The sensitivity analysis indicates the water released from the deposited tailings during post closure periods could range from 5.2 Mm^3 (Case 4) to 18.7 Mm^3 (Case 1) for a period over 300 years. The coefficient of consolidation is the predominating influence parameter since the higher the coefficient of consolidation, the more water would be released during deposition, and less water would released during post-closure.

Based upon the column and consolidation tests described in GHD 2016 (which resulted in an average coefficient of consolidation of 2m^2/month) and the 2017 Rowe Cell test (which found a cv range from 1.5m^2/month to 9.8m^2/month), Case 1 is considered to be the case with a lower bound value of c_v and Case 4 as an upper bound value of c_v. Based upon the testing undertaken to date, we recommend that Case 2 can be considered as a reasonable base case, with an average c_v of 2.0 m^2/month (i.e. 24.0 m^2/year) to represent the field conditions of in-pit deposition.

5 References

GHD (2016) Tailings Deposition into Open Pit – Consolidation Modelling and Deposition Concept, 3 November 2016 (document 32/1747605/65221)

Li, A.L., Been, K., Wislesky, I, Eldridge, T. and Williams, D. (2012). Tailings initial consolidation and evaporative drying after deposition. The International Seminar on Paste and Thickened Tailings, Paste 2012, 16–19 April, 2012, Sun City, South Africa, pp.25-42.

Kind Regards
GHD Pty Ltd

Allen LI
Principal Geotechnical Engineer

Matthew Daley
Project Manager

Attachments:

- *Fugro Rowe Cell Consolidation Test results (2 pages)*

Client: GHD Pty Ltd
Project: In-Pit Tailings Deposition Modelling
Location: McArthur River Mine
Sample No.: Tailings Sample 32-1747605-2017

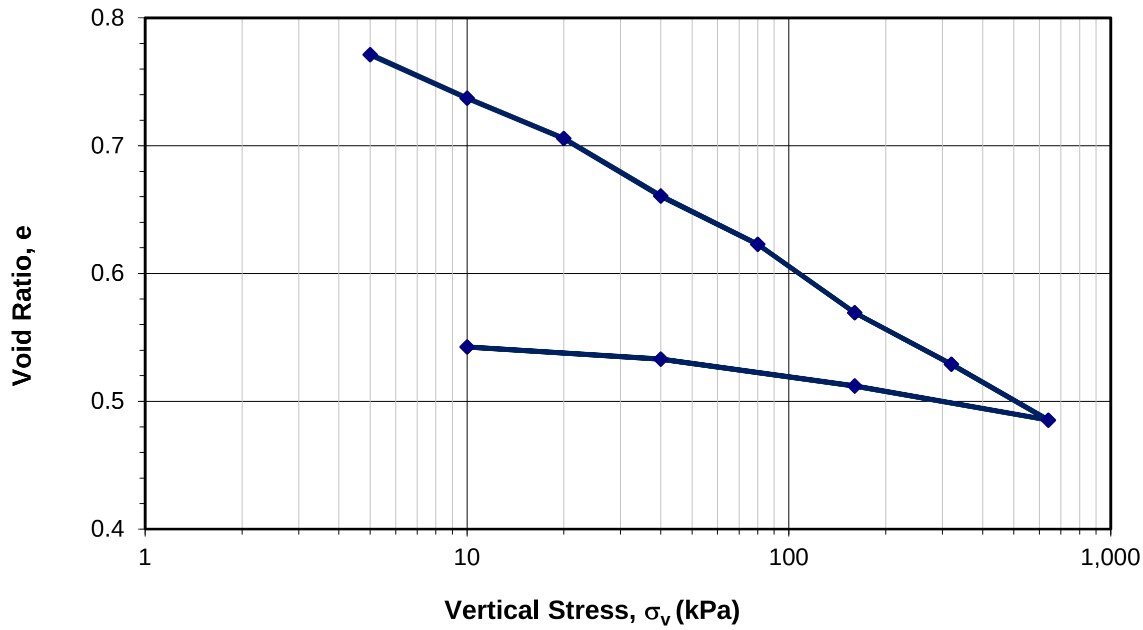
IPO Number: 2017-028
Sample ID: 2017-028-001R
Borehole ID: -
Depth: -

Test Details:	
Test ID:	MRM-ROWE01R
Tested By:	RC
Date:	07/11/2017
Checked By:	TC
Date:	22/11/2017

Sample Details:	Initial	Final
Sample Diameter (mm) :	254.0	254.0
Sample Height (mm) :	31.01	20.34
Dry Density (t/m^3) :	1.26	1.93
Moisture Content (%) :	27.9	17.2
Soil Particle Density (t/m^3) :	2.97	

ROWE CELL CONSOLIDATION TEST
Test Method: agLAB Test Procedure aL-PT39

Stage		**s_v**	**e**	**c_v**	**m_v**	**k**	
						Calculated	Measured
		kPa		**m^2/year**	**m^2/kN**	**m/sec**	**m/sec**
Seating	0	2.5	0.793	-	-	-	-
Loading	1	5	0.771	-	-	-	-
	2	10	0.737	17.9	3.84E-03	2.13E-08	-
	3	20	0.706	31.2	1.82E-03	1.77E-08	1.47E-08
	4	40	0.661	35.2	1.32E-03	1.44E-08	1.25E-08
	5	80	0.623	59.6	5.71E-04	1.06E-08	9.81E-09
	6	160	0.569	64.4	4.12E-04	8.26E-09	7.77E-09
	7	320	0.529	110.8	1.60E-04	5.52E-09	6.58E-09
	8	640	0.485	117.3	8.94E-05	3.26E-09	4.88E-09
Unloading	9	160	0.512	-	-	-	-
	10	40	0.533	-	-	-	-
	11	10	0.542	-	-	-	



In-Pit Tailings Deposition Modelling
Rowe Cell Consolidation

Job No.LAB237

Figure A-1

Permeability Measurements:

Sample Area (mm^2) 50655

Vertical stress	Flow rate	ΔH	ΔH	Sample thickness	Hydraulic Gradient	Permeability, k	Permeability, k
(kPa)	(mm3/min)	(kPa)	(m)	(mm)	i	(m/min)	(m/sec)
20	604.3	3	0.306	22.50	13.6	8.78E-07	1.46E-08
40	917.5	5	0.510	21.90	23.3	7.78E-07	1.30E-08
80	601.0	5	0.510	21.40	23.8	4.98E-07	8.30E-09
160	937.1	10	1.019	20.70	49.3	3.76E-07	6.26E-09
320	914.8	10	1.019	20.17	50.5	3.57E-07	5.95E-09
640	734.4	10	1.019	19.59	52.0	2.79E-07	4.64E-09

Vertical stress	Flow rate	ΔH	ΔH	Sample thickness	Hydraulic Gradient	Permeability, k	Permeability, k
(kPa)	(mm3/min)	(kPa)	(m)	(mm)	i	(m/min)	(m/sec)
20	608.8	3	0.306	22.50	13.6	8.84E-07	1.47E-08
40	1761.4	10	1.019	21.90	46.5	7.47E-07	1.25E-08
80	1420.0	10	1.019	21.40	47.6	5.89E-07	9.81E-09
160	1745.0	15	1.529	20.70	73.9	4.66E-07	7.77E-09
320	1662.0	15	1.529	20.17	75.8	4.33E-07	7.21E-09
640	927.5	15	1.529	19.59	78.1	2.35E-07	3.91E-09

Vertical stress	Flow rate	ΔH	ΔH	Sample thickness	Hydraulic Gradient	Permeability, k	Permeability, k
(kPa)	(mm3/min)	(kPa)	(m)	(mm)	i	(m/min)	(m/sec)
40	2605.5	15	1.529	21.90	69.8	7.37E-07	1.23E-08
80	2364.3	15	1.529	21.40	71.4	6.53E-07	1.09E-08
160	2618.0	20	2.039	20.70	98.5	5.25E-07	8.74E-09
320	2021.8	20	2.039	20.17	101.1	3.95E-07	6.58E-09
640	1543.4	20	2.039	19.59	104.1	2.93E-07	4.88E-09