

Dewatering of Gold Tailings Using Vacuum Enhanced Wellpoint System

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Abstract:

Giant Mine was an open pit and underground gold mine located 5 km north of the City of Yellowknife, Northwest Territories, Canada. As part of the closure and remediation plan, one of the tailings containment areas will be excavated and relocated to reduce footprint of the area to be covered. Tailings excavation and relocation will require dewatering of groundwater, excavation of tailings, transportation of excavated tailings for disposal. At disposal locations, the tailings will need to be conditioned to further lower water content for placement and compaction. A field dewatering trial was completed to evaluate the potential use of the vacuum enhanced dewatering system during the closure and remediation construction.

This paper presents the assessment of groundwater dewatering options, the design and operation of the dewatering trial, the results of monitoring data analysis, and the interpretation of data associated with the dewatering trial that was completed for the Giant Mine.

Introduction

Giant Mine was an open pit and underground gold mine located 5 km north of the City of Yellowknife, Northwest Territories, Canada. Giant Mine started production in 1949 and ceased operations in 2004. During the operations, tailings were hydraulically deposited within the tailings containment areas from spigots located at the perimeter dams. Tailings containment areas include the North Pond, Central Pond, South Pond, Settling Pond, Polishing Pond, and Northwest Pond (Figure 1). As part of the closure and remediation plan, tailings in the South Pond will be excavated and relocated to reduce footprint of the area to be covered. Tailings in the South Pond extend to the depth of up to 16 m, with an average thickness of approximately 11 m. Groundwater table in the South Pond varies from approximately 0.8 m to 10.7 m, with an average depth of 3.9 m.

Saturated tailings are susceptible to liquefaction. Remediation of the South Pond will require dewatering of groundwater, excavation of tailings and transportation of excavated tailings to Central Pond and North Pond for disposal. At disposal locations, the tailings will need to be

conditioned to further lower water content for placement and compaction. This could be achieved through more traditional methods such as windrows, frequent discing or mixing with dry materials. To optimize efficiency during the construction, it is important that conditions within the area of excavation and construction be workable. Both groundwater lowering and surface water control are necessary.

A tailings dewatering field trial program was completed to evaluate the potential for groundwater dewatering in South Pond tailings, which could be considered during the closure and remediation construction. The primary objective of the field trial program was to assess the effectiveness of the vacuumed enhanced dewatering system to lower the tailings water content and increase tailings strength for the excavation, transportation and placement of tailings.

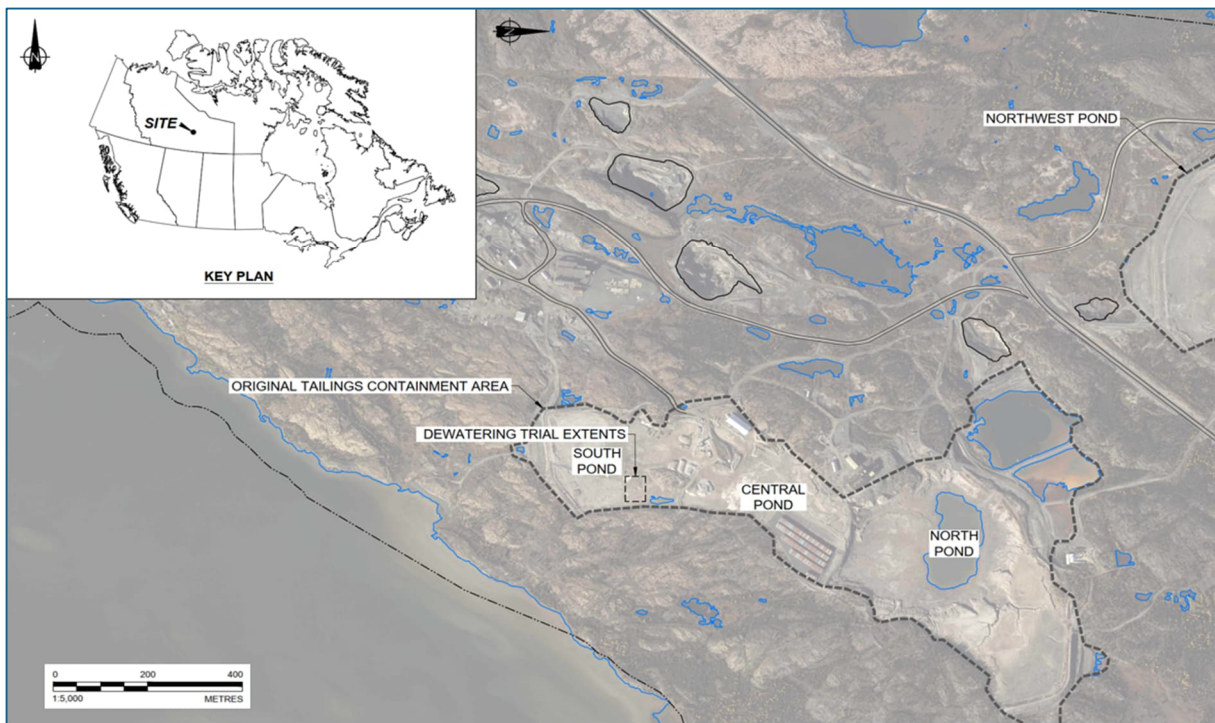


Figure 1 : Site location plan

Tailings Properties

Tailings were hydraulically deposited (slurry) from spigots with varying locations along the perimeter of the dams. This method typically results in segregation of the tailings, with the coarsest particles settling out first, and the finer particles settling out farther from the spigot point. A varied distribution of tailings gradation is due to the combined effects of frequent changes in spigot locations and the segregation of tailings.

Tailings consist of layers of silt, clayey silt, silty clay, sandy silt, silty sand, and sand. The in situ tailings can be divided into two groups:

- Fine Tailings – described as silt, clayey silt, and silty clay.
- Coarse Tailings – described as sandy silt, silty sand, and sand.

The tailings samples were found to be non-plastic, except some with plasticity indices ranging between 1 and 3. Specific gravity was 2.83. Natural water contents vary from 10% to over 40%.

Figure 2 shows particle size distribution test results completed for tailings, including those obtained from the dewatering trial area. No clear zones of coarse tailings and fine tailings were observed in the area of dewatering field trial. The particle size distribution (PSD) curves obtained from the dewatering field trial are consistent with the curves measured during previous investigations at the Giant Mine site. Particle sizes are poorly graded. The sand content was between 0% and 78%, and fines content was between 22% and 100%. Based on the hydrometer results, the majority of the fines were silt sized particles.

Figure 3 presents the Soil-Water Characteristic Curve (SWCC) test results, one on a sample of fine tailings and one on a sample of coarse tailings. The particle size distributions of the samples used for the SWCC testing are at the fine and coarse bounds of particle size distributions, as shown in Figure 2. The results of SWCCs indicate that the air entry value varies over a wide range, from 4 kPa to 150 kPa.

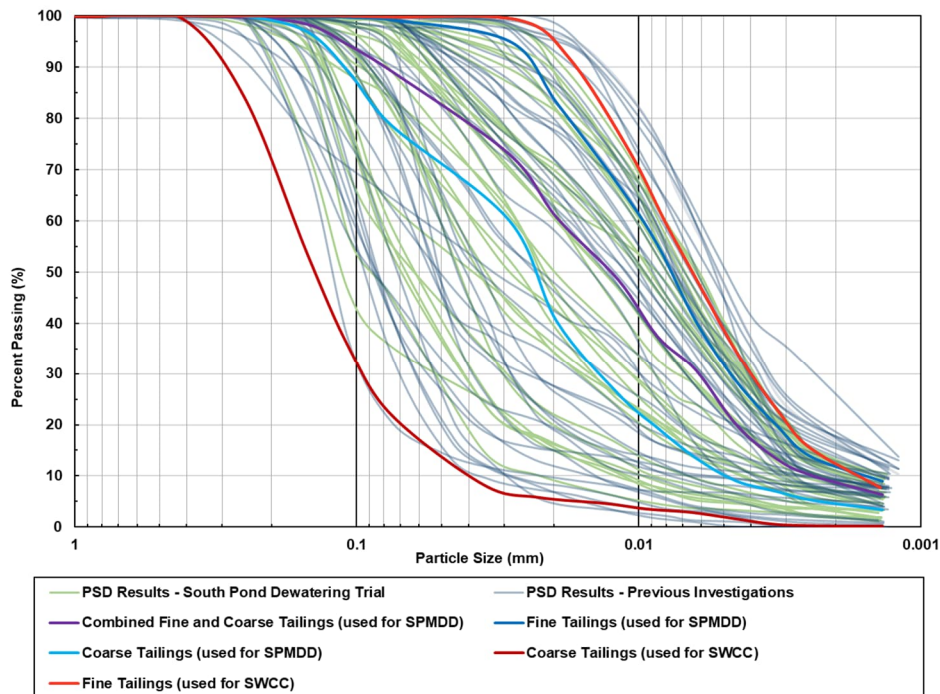


Figure 2: Particle size distribution.

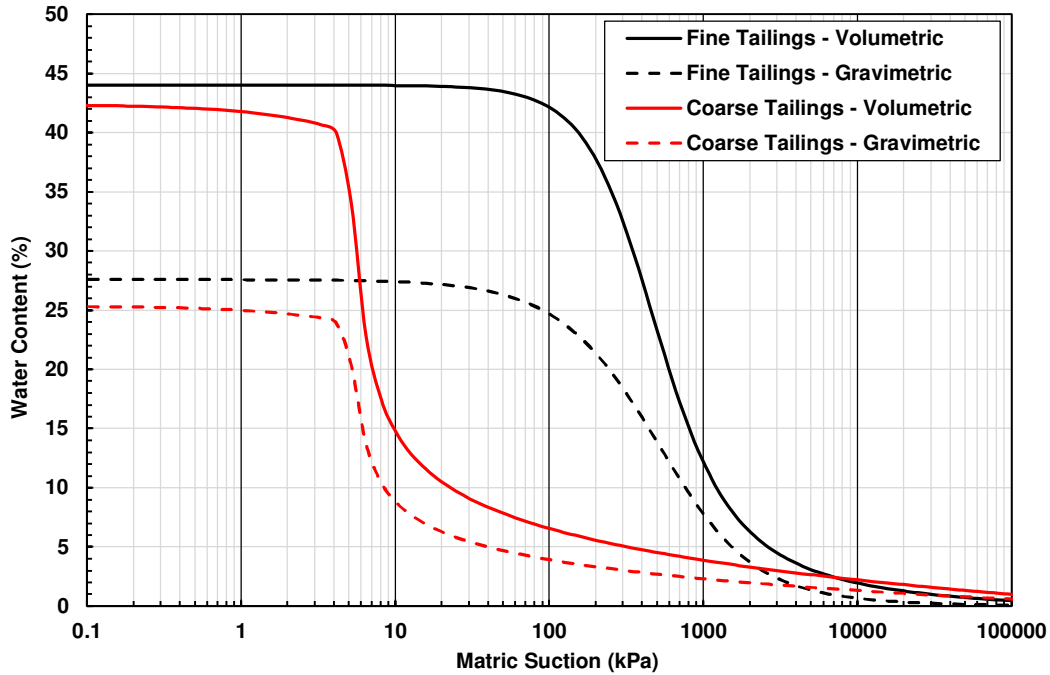


Figure 3: Soil-water characteristic curves.

Eight slug tests (rising and falling head tests) were conducted in standpipe piezometers installed in the South Pond. The estimated horizontal hydraulic conductivity of tailings from these slug tests varied from 1.3×10^{-7} m/s to 1.8×10^{-6} m/s. Figure 4 compares the tailings hydraulic conductivity estimated from the slug test results with those previously obtained from Cone Penetration Test (CPT) results. The boxes in this figure represents the first to third quartiles of the results. The estimated horizontal hydraulic conductivity values fall within the range of hydraulic conductivity values obtained from CPT results.

Three standard proctor tests were carried out on tailings samples. One was carried out on the samples of fine tailings, one on coarse tailings, and one on combined samples of fine and coarse tailings. Particle size distribution test was also completed on each of the samples that was used for proctor test. The particle size distributions of the composite tailings samples used for the tests are presented in Figure 2. The results of the proctor tests are presented in Figure 5.

Preliminary Assessment of Dewatering Options

Various groundwater lowering methods have been successfully used for construction dewatering in engineering practice. Figure 6 presents the tentative ranges of groundwater lowering methods that could be considered based on soil PSD [1]. Figure 6 also shows the PSD curves for fine tailings and coarse tailings from South Pond. This figure suggests that drainage from pumped wells and wellpoints can be considered for the South Pond tailings.

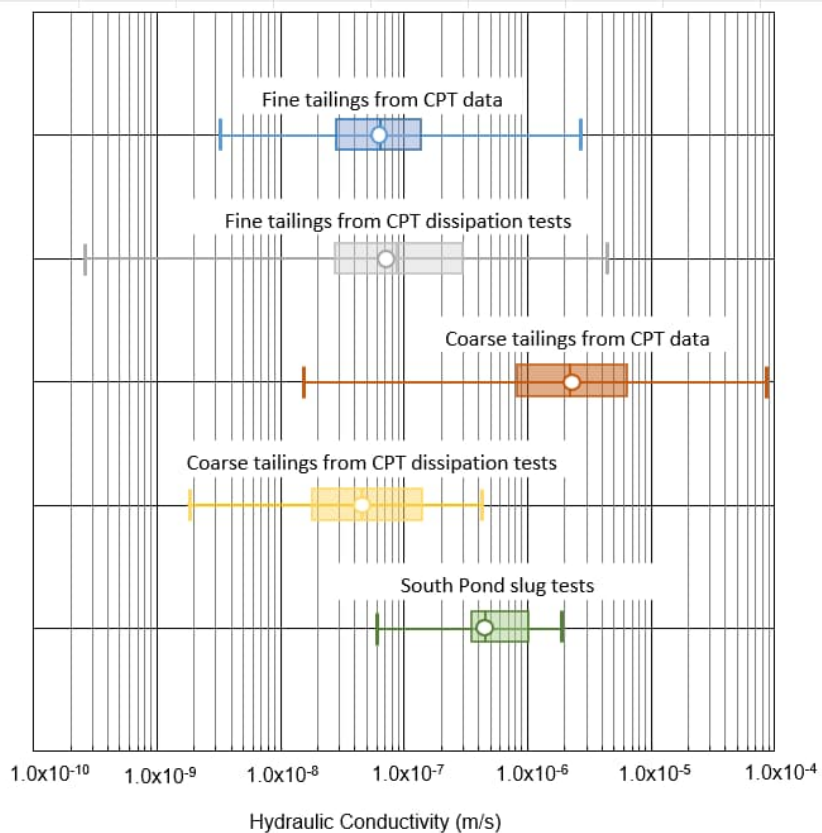


Figure 4: Saturated hydraulic conductivity

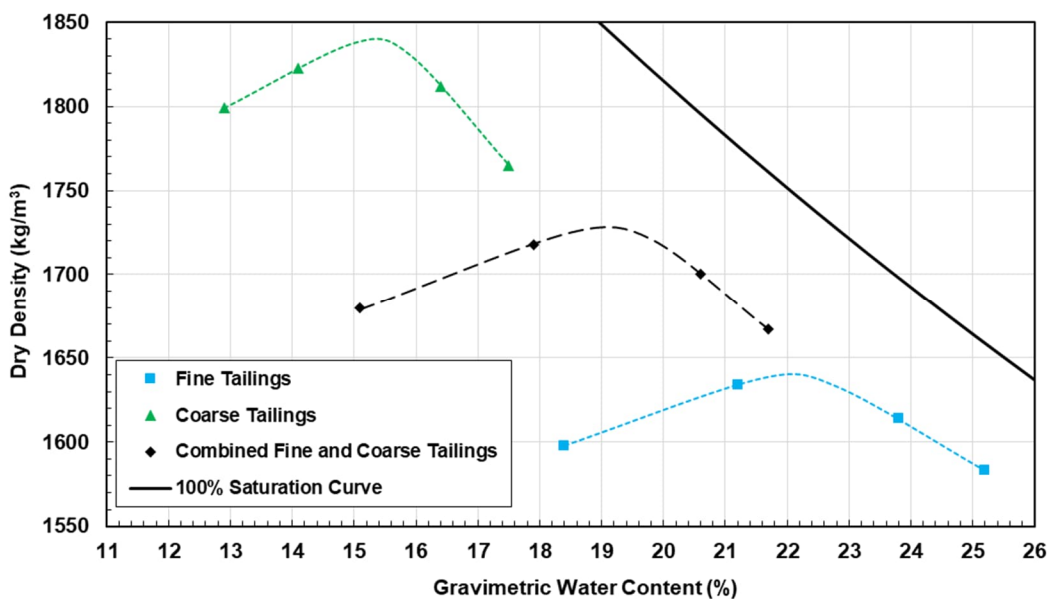


Figure 5: Tailings water content – dry density relationship.

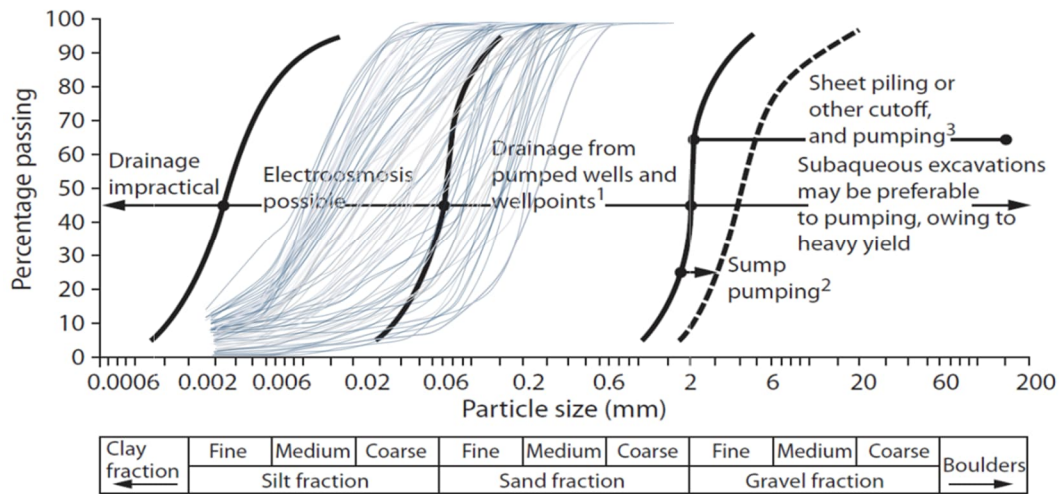


Figure 6. Tentative range for groundwater lowering methods [1].

Notes on Figure 6: Colored lines are PSD curves of South Pond tailings; (1) wellpoints in fine sand require vacuum; (2) zone may be extended in finer soils by using large sumps with gravel filters; (3) to reduce the high water pressure on sheet piling, it may be preferable to control pumping as excavation proceeds and to install the support system as the water level is lowered.

Figure 7 presents a range of application of pumped wells for the groundwater control based on soil hydraulic conductivity and required drawdown. As the hydraulic conductivity of tailings vary in a wide range, from 2.5×10^{-10} m/s (for fine tailings) to 8.4×10^{-5} m/s (for coarse tailings), and required drawdown for the South Pond tailings is approximately 10 m, either vacuum enhanced well points or ejector methods could be considered.

Gravity drainage would dominate in soils of hydraulic conductivity of greater than approximately 5×10^{-5} m/s ([2] and [3]). For soils of lower hydraulic conductivity, top of the wells can be sealed, a partial vacuum can be applied to assist drainage. A sealed wellpoint system operated by vacuum tank pump may be effective in soils of permeability down to about 1×10^{-6} m/s such as the South Pond tailings. Ejectors installed in sealed wells generate a vacuum in the well and can be effective in soils with a hydraulic conductivity as low as 1×10^{-7} m/s. In low hydraulic conductivity soils, the layering system of coarse and fine materials has a great influence on the performance of dewatering systems. At the South Pond, the tailings structure consists of alternating layers of coarse and fine tailings, the drainage would be improved because the layers of coarse tailings will more rapidly drain the adjacent layers of fine tailings.

Based on the stratigraphy and hydraulic properties of the tailings, the conventional deep dewatering wells and trench sump pump methods with gravity draining of groundwater table would not be effective. A vacuum enhanced wellpoint system could be used to achieve a drawing down of 5 to 6 m in a month of dewatering.

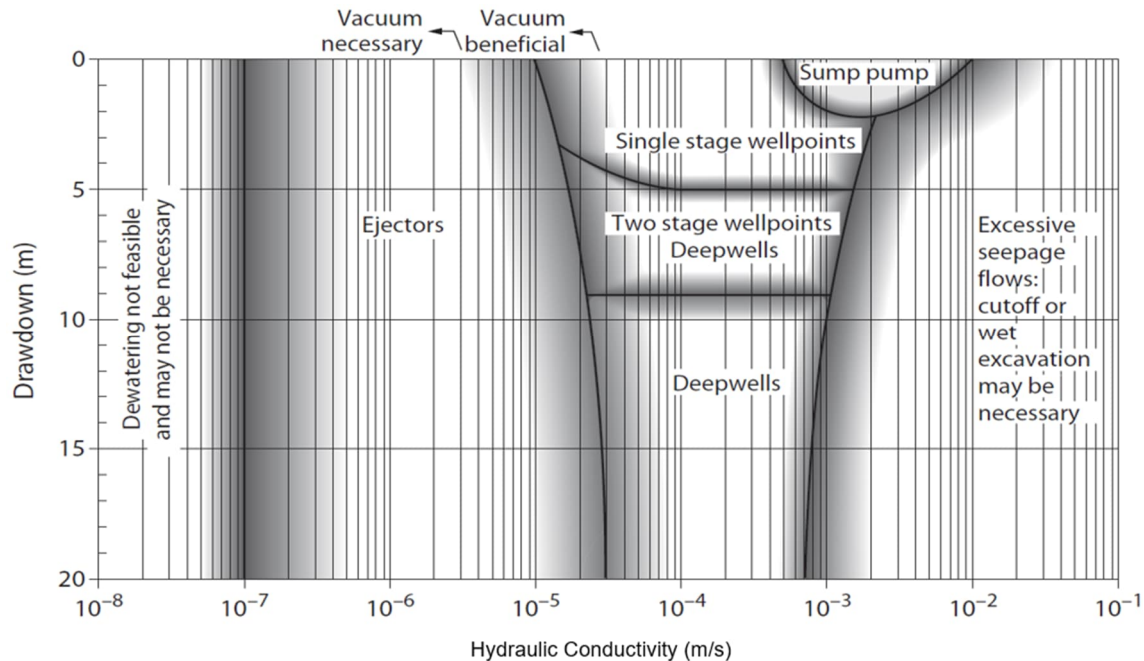


Figure 7: Range of application of pumped well groundwater control techniques [1].

Vacuum Enhanced Wellpoint Method

A wellpoint system consists of a series of closely spaced small diameter wellpoint water wells. The wellpoints are connected through a manifold to the suction side of a suitable pump. The applied vacuum from the pump sucks the groundwater from the surrounding ground through the wellpoint screens, into the riser pipes, up into the header main and to the pump intake. If necessary, the annulus around the wellpoint raiser at the surface zone would be sealed with low permeability material such as bentonite to prevent air leaks and improve the rate of drainage. The application of vacuum enhanced wellpoints is constrained by the physical limits of suction lift and hydraulic properties of the ground. Ideally, the header main should be as close as possible to the static groundwater level to minimize the amount of suction lift. Figure 8 provides a sketch of traditional vacuum enhanced wellpoint system for an excavation [4]. For the tailings dewatering, the application will be similar. Rather than installing around the perimeter of the excavation, rows of wellpoints would be used to dewater the tailings. The wellpoints would then be removed prior to excavation.

Design of The Dewatering Trial

As a part of the dewatering field trial design, seepage analysis was completed to evaluate the configuration of vacuum enhanced wellpoints to effectively dewater of the saturated tailings in the South Pond. The result of the analysis provides indication of wellpoint spacing, time required for dewatering, and potential pumping rates.

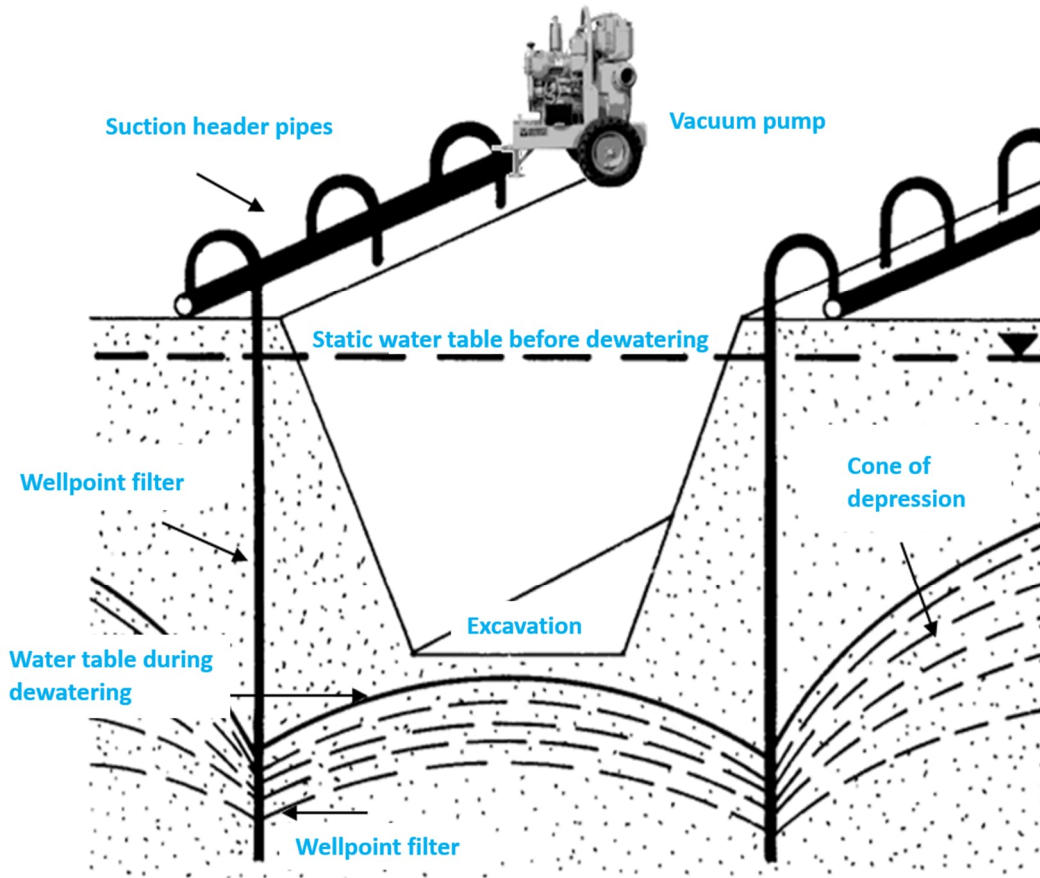


Figure 8: Traditional vacuum enhanced wellpoint setup [4]

Seepage analysis was conducted using a finite element, axisymmetric or two-dimensional transient, saturated/ unsaturated seepage model. Axisymmetric model was used to evaluate the required wellpoint spacing within a row. A two-dimensional model was used to evaluate the required spacing between wellpoint rows.

Tailings dewatering and excavation would be completed in the same construction season; therefore, the target dewatering time for each stage/area used in the analysis was approximately a month or less. Lowering water table in tailings to about 4 m was targeted for the effective use of construction equipment.

Combined hydraulic conductivity values of tailings (Figure 4) were considered for the analysis, as it would not be practical to differentiate between coarse and fine tailings zones within the South Pond. The presence of variable grain sizes and bedding would result in anisotropy of the tailings. The anisotropy is represented by the ratio of vertical hydraulic conductivity to horizontal hydraulic conductivity (k_v/k_h). Parametric analyses were completed to evaluate the effect of variations in the field particle size distribution (PSD) of coarse tailings and fine tailings,

and the impact of hydraulic conductivity variability on the wellpoint spacing, and time needed for dewatering.

The results from the seepage analysis indicate that vacuumed enhanced wellpoints could potentially be used for dewatering of the saturated tailings. However, the effectiveness of the method is dependent on the overall in situ characteristics of the tailings. This includes the distribution/layering of fine and coarse tailings, the resulting hydraulic conductivities, and the hydraulic conductivity ratio. A conservative (closer spaced) well spacing should be considered to account for the uncertainty and variability of the in situ conditions, as well as well efficiency effects that the model does not account for. To lower the water table to a depth of 4 m, the design of the dewatering field trial considered the following:

- Wellpoints should be installed to the depth of up to 6 m with a screen section of approximately 1 m at the lowest portion of the well.
- Wellpoint spacing within a wellpoint row should be in a range of 1 m to 2 m.
- Wellpoint row spacing should be in a range of 15 m to 30 m.
- The expected time to lower the water table by approximately 4 m is in a range of two to four weeks.

Dewatering Trial Operation and Monitoring

A dewatering field trial was completed in the fall of 2022. The South Pond dewatering trial area was located on the northeast portion of the South Pond (Figure 1). The trial layout is shown in Figure 9.

Dewatering Trial Layout

The layout is divided into four trial zones, denoted as Zones A through D, considering two wellpoint spacings and two wellpoint row spacings as summarized in Table 1 and presented in Figure 10. The wellpoint system consisted of three wellpoint rows, with two sections of wells in each row, for a total of six trial sections, denoted as Section 1 through 6. The three rows were oriented east-west and are referred to as the south, center and north dewatering rows. Each row consisted of one section of ten 2.5 m spaced wellpoints and one section of eighteen 1.5 m spaced wellpoints. The spacing between the rows was 30 m between the south and center rows and 15 m between the center and north rows. A total of 84 wellpoints were installed in the six wellpoint sections.

Standpipe piezometers and vibrating wire piezometers (VWP) were installed along two instrumentation cross sections, cross section A and cross section B. Cross section A was positioned through the middle of Zone A and Zone C, which had a 1.5 m wellpoint spacing within three sections. Cross section B was through the middle of Zone B and Zone D, which had a 2.5 m wellpoint spacing within three sections.

Table 1: Dewatering Trial Configuration

Zone	Wellpoint Spacing within Row (m)	Wellpoint Row Spacing (m)	Wellpoint Sections
A	1.5	15	1 and 3
B	2.5	15	2 and 4
C	1.5	30	3 and 5
D	2.5	30	4 and 6

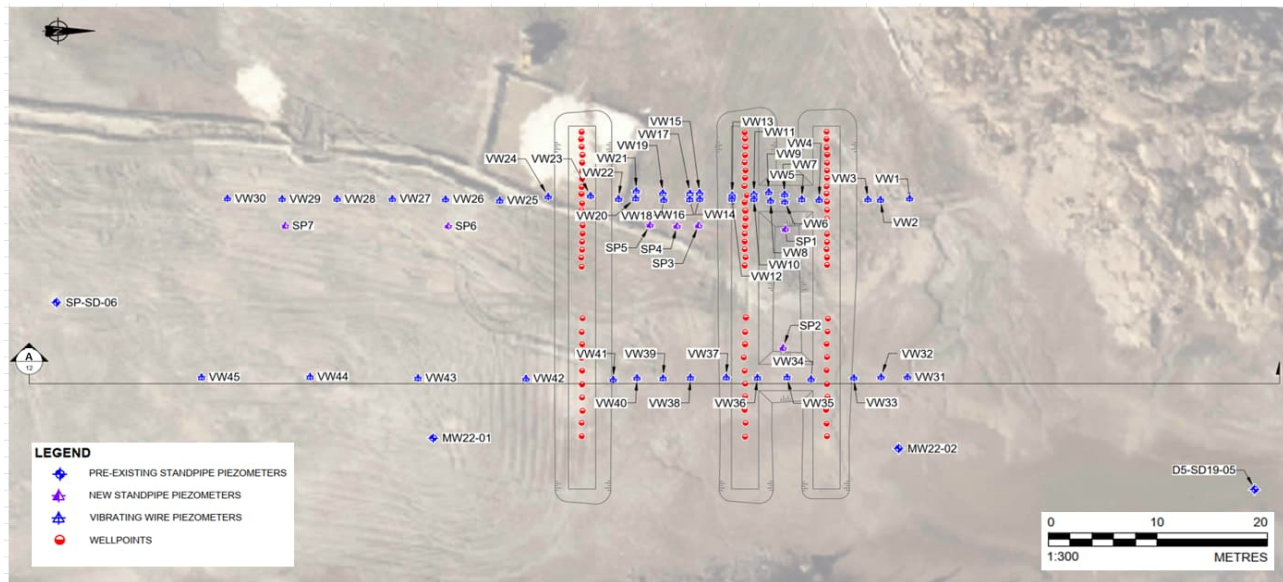


Figure 9: Dewatering trial location and instrumentation plan

Dewatering Trial Operation

The dewatering trial operation ran from 15 September to 13 October 2022. The contractor continuously monitored the dewatering system, recorded flow and suction data, performed regular maintenance, and made system adjustments as needed. Throughout the trial, sections were periodically shut off for maintenance tasks such as cleaning silt out of header pipes and exchangers. Maintenance shutdowns typically did not last more than 1 to 2 hours.

During the dewatering operation several dewatering wellpoints were found to be non-productive. Investigations carried out during the trial found that tailings had silted up the non-productive wellpoints. It was assumed, and later confirmed on extraction of the wellpoints, that the screen had been damaged allowing tailings to enter the well. Non-productive wellpoints were shut off from the system during the operation. Discharge water was observed to be clear after the non-productive wellpoints were disconnected.

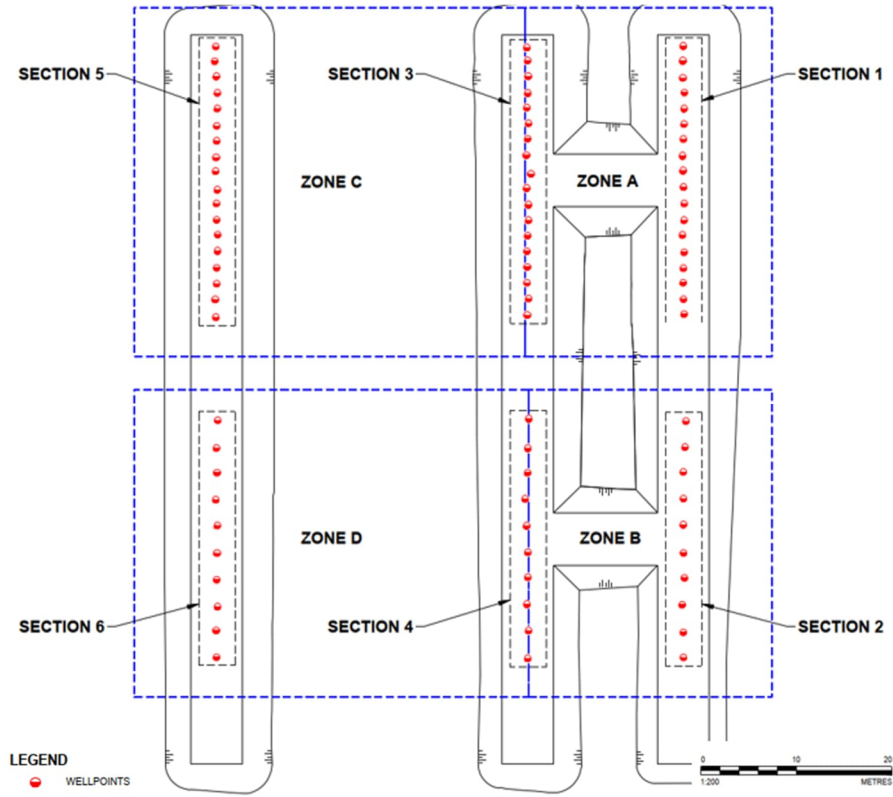


Figure 10: Dewatering trial zone delineation



Photograph 1: Aerial view of the dewatering trial area

Water Flow Data

Daily groundwater extractions from the individual wellpoint sections were available from flowmeter data. In addition, total discharge flow rates to Central Pond were also checked using a “bucket test” by timing the filling of a bucket from the discharge line. Table 2 presents the estimated extracted water volumes for each section and for the entire dewatering system over the course of the 28-day trial.

Table 2: Extracted Water Volume over 28-day Dewatering Field Trial

Dewatering Section	Zone	Wellpoint Spacing (m)	Average Daily Volume (L)	Average Daily Volume per Functioning Wellpoint (L)	Volume of Groundwater Extracted During Trial (L)
Section 1	A	1.5	2,158	216	62,590
Section 2	B	2.5	6,094	666	176,712
Section 3	A, C	1.5	3,004	234	87,117
Section 4	B, D	2.5	2,651	522	76,888
Section 5	C	1.5	7,188	1,032	208,450
Section 6	D	2.5	15,025	1,684	435,729
Total					1,047,486

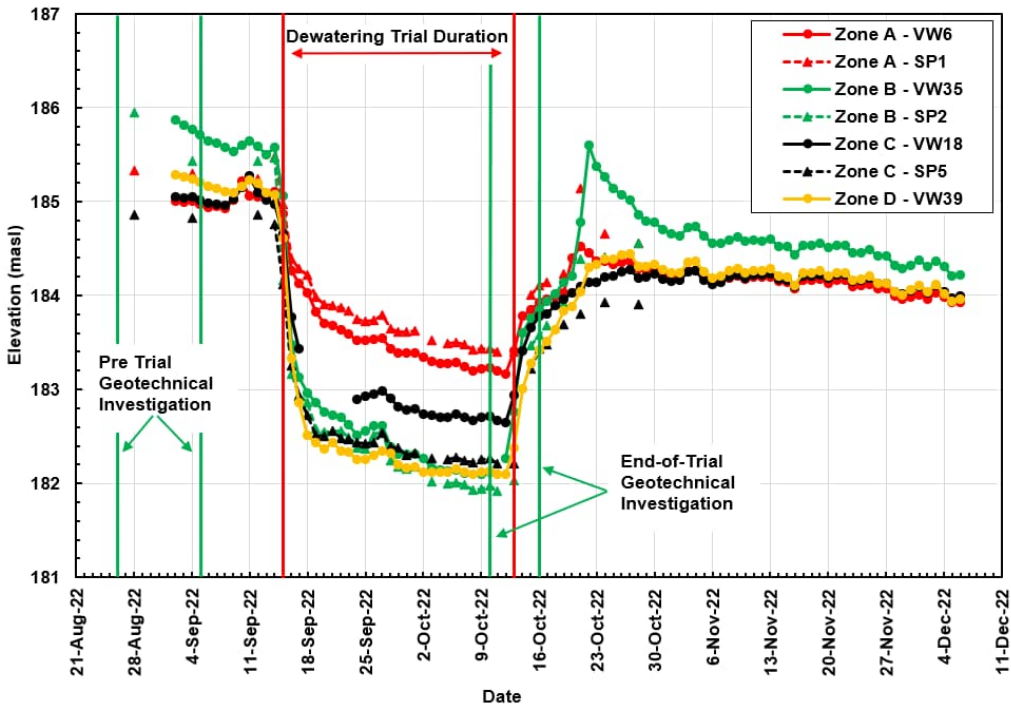


Figure 11: Measured piezometric elevations over time by trial zone

Groundwater Monitoring

Groundwater monitoring data was collected in the leadup to the trial, during the trial, and during the groundwater recovery period following the trial operation. Monitoring of the recovery of the groundwater table began immediately following the end of the dewatering operation. Figure 11 presents the instrumentation that was closest to the centre of each of the four dewatering trial study zones.

Test Pit Investigation

Test pits were excavated prior to and following the trial to log the stratigraphy, obtain samples for laboratory testing, and observe the behavior of the excavated tailings and test pit wall stability conditions.

Field observations during trench excavation and backfill, installation of instrumentation, and test pitting indicate that tailings in saturated condition are susceptible to construction equipment loading and vibration. Saturated tailings were observed to be unworkable. Excavation in saturated tailings resulted in a loss of bearing capacity for excavator and sloughing conditions in test pits. Photograph 2 showing the conditions observed during the excavation of a test pit prior to the dewatering trial. Saturated tailings in the pit appeared in a flowing condition, and the excavator started to sink into tailings near the test pit location.



Photograph 2: Unworkable conditions prior to dewatering, sinking of equipment

Following the trial, the surface of the tailings was observed to be more stable when heavy equipment was operating at surface. During the excavation of a test pit following the dewatering operation, the tailings remained relatively stable during the excavation as shown in the photograph 3, this test pit could extend to a depth of 5.2 m without collapsing. Dewatering of saturated tailings has resulted in an increase in the strength of the tailings reflected in improved excavator trafficability and stability of excavations in the tailings. As a result of the increase in tailings strength, the practical maximum depth of test pit excavations increased from 2 m before start of trial to up to 5 m after the dewatering trial operation.



Photograph 3: Workable conditions following dewatering operation, test pit excavated to 5.2 m depth

Data Analysis and Interpretation

A two-dimensional, saturated-unsaturated, transient seepage model was developed and calibrated using the available data from the dewatering trial to estimate the hydraulic properties of the tailings and to evaluate the amount of drawdown, extracted groundwater volume, and potential change in tailings conditions (i.e., water content and degree of saturation) versus time to support the excavation, transportation, and placement.

Cross Section A, cutting through the middle of Zone B and Zone D (i.e., between wellpoint Sections 2, 4 and 6) was selected for the simulation. Location of Cross Section B is shown in

Figure 9. Tailings surface, soil stratigraphy, initial groundwater table and piezometric elevations recorded along this cross section are shown in Figure 12.

The following assumptions were considered:

- The modelling simulations assumed that changes to the groundwater conditions in the South Pond during the dewatering trial were dominated by the wellpoint dewatering.
- Initial groundwater conditions in the South Pond were hydrostatic.
- The area of Zone B and Zone D was bounded by bedrock outcrops on the north and along the east side. Tailings thickness (i.e., the tailings and foundation soil elevation) varied along the cross section. For practical engineering purposes, the flow system toward the wellpoint rows could be reasonably represented by a two-dimensional seepage model. The effect of radial flows toward the wellpoint rows, particularly from the south side of the trial area was not considered.
- Recharge from tailings surface (i.e., precipitation and evaporation), leakage through the tailings/foundation soils contact, and the effect of groundwater elevation fluctuation on the south extent and north extent of Cross Section B during the dewatering trial have only minor impact to groundwater system during dewatering operation.

Because of the complexity of the tailings conditions, stratigraphy and groundwater flow regime in the South Pond, it is not realistic to have similar matches at the three wellpoint sections with the same set of parameters. The goal of the numerical analysis is to find one set of tailings properties (e.g., SWCC, saturated horizontal hydraulic conductivity k_h , and vertical hydraulic conductivity to horizontal hydraulic conductivity ratio, k_v/k_h) that provide the best fit to the available flow rate data and piezometric elevation data. A range of parameters can then be applied in the same manner to investigate the sensitivity of the system.

Table 1: Summary of Modelling Scenarios

Modelling Scenario	Tailings Zone between Wellpoint Row	Wellpoint Section
1	D	6
2	B	2
3	B, D	4
4	B, D	2, 4, 6

The seepage models were first developed and calibrated for individual wellpoint sections and zones (e.g., sub-areas) associated with Cross Section B to evaluate the potential range of field hydraulic properties. A model considering the entire Cross Section B was then developed and calibrated. There were three models (Scenarios 1 to 3) of sub-areas for three wellpoint sections (Sections 6, 4 and 2) and one scenario (Scenario 4) for the entire three wellpoint sections. Table 1 provides the dewatering zone and wellpoint sections considered for each scenario. Tailings properties that provide the best fit to the field data from Scenario 4 would be considered as representative bulk properties for the tailings in the South Pond. The geometry of Scenario 4 was also used for modelling of the recovery process and parametric study.

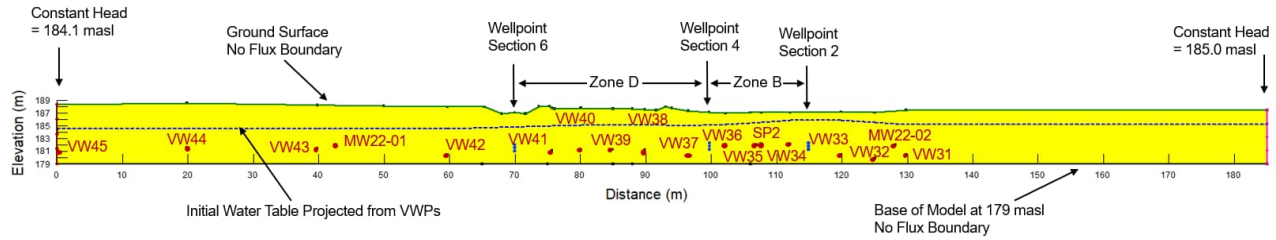


Figure 12: Model geometry and boundary conditions for Scenario 4

Individual flow rates from wellpoint Sections 2, 4 and 6 were used for modelling calibration. The observed flow rates are the total from all the wells in each 22.5 m long wellpoint section. For the use in the two-dimensional model with a unit thickness of 1 m, the recorded flow rates were divided by 22.5 to estimate the flow rate per metre.

Piezometric elevation data recorded along Cross Section B was used to calibrate the model (Figure 12). VWP's which span most of the cross section include VW31 to VW45. Five standpipe piezometers, located close to the model cross section, can be projected onto the section to compare the observed hydraulic head response over time.

Range of Soil Properties Used for the Model Calibration

In unsaturated soils, the rate of water flow is significantly affected by the degree of saturation (or water content) of the soil. Water flows through the pore spaces filled with water; therefore, the percentage of the voids filled with water is an important factor [5]. As soil becomes unsaturated, air replaces some of the water in the large pores, which causes the water to flow through the smaller pores, resulting in increased tortuosity of the flow path. Increases in negative pore-water pressure (i.e., suction) in the soil leads to further decreases in the pore volume occupied by water. As a result, the hydraulic conductivity with respect to the water phase decreases as the space available for water flow reduces. The SWCCs that were measured through laboratory tests (see Figure 3) are considered to represent the upper bound and lower bound of SWCCs for the tailings in the South Pond. This consideration is based on the measured particle size distribution curves of the tailings samples (see Figure 2). Using the two curves as constraints, a range of SWCCs were created and adjusted to find the best fit to field data (e.g., hydraulic head and water flow). Figure 13 presents the SWCCs (described using Fredlund and Xing equation [6]) for two tailings samples that were tested and the assumed Tailings 1 to Tailings 5 that were utilized during analysis to find the best fit properties. It is assumed that tailings become finer from Tailings 1 to Tailings 5.

The range of hydraulic conductivity values from 8.3×10^{-7} m/s to 6.4×10^{-6} m/s (i.e., 1st quartile to 3rd quartile shown in Figure 4) was considered. On a larger scale, layers of coarse tailings and features with higher hydraulic conductivity would govern the overall horizontal hydraulic conductivity of tailings. The hydraulic conductivity of the tailings varies in vertical and horizontal directions due to the layered effect of the tailings. The ratio of vertical hydraulic

conductivity to horizontal hydraulic conductivity k_v/k_h can be estimated by the range of hydraulic conductivity value observed. The expected range for the k_v/k_h ratio was considered from 0.1 to 0.01 for the numerical analysis.

The hydraulic conductivity functions were estimated from the saturated hydraulic conductivity and the corresponding SWCC using Fredlund et al. (1994) method [7]. Figure 14 presents the estimated hydraulic conductivity functions for Tailings 1 to Tailings 5 with a saturated hydraulic conductivity of 2×10^{-6} m/s. As shown in Figure 13, the unsaturated hydraulic conductivity of coarse tailings (i.e., Tailings 1) is much smaller than that of fine tailings (i.e., Tailings 5) at a suction higher than 10 kPa. With increasing of matric suction in the tailings, the unsaturated hydraulic conductivity of the tailings decreases. For example, the tailings hydraulic conductivity at 60 kPa suction is over one order of magnitude less (for Tailings 5, fine tailings) and four order of magnitude less (for Tailings 1, coarse tailings) than the saturated hydraulic conductivity.

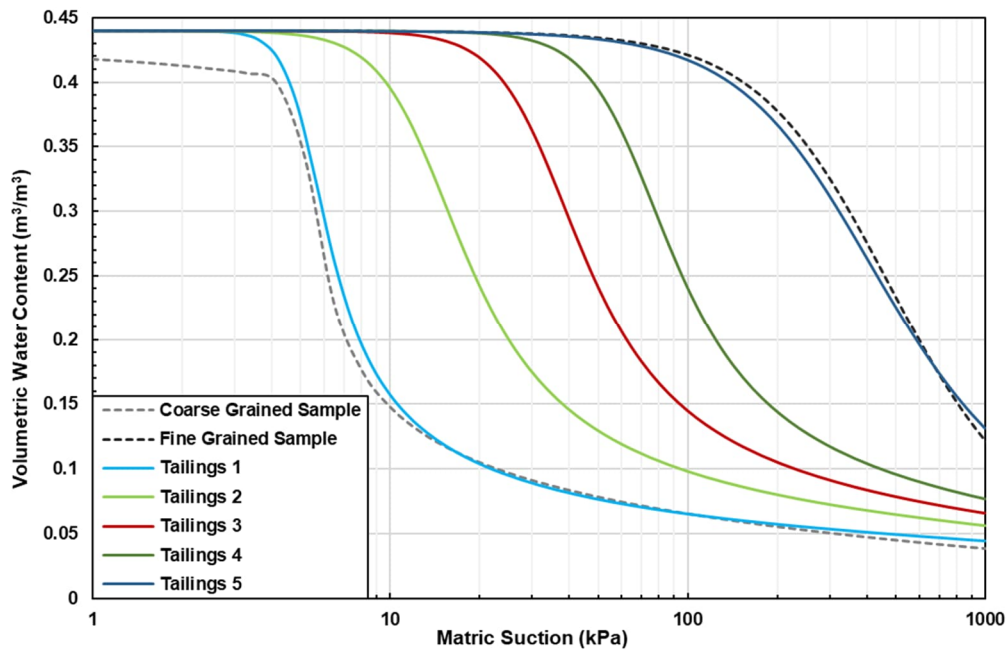


Figure 13: Range of SWCCs used in model calibration

Range of Suction Applied at Wellpoints

The pump suction recorded during the dewatering operation was over 70 kPa. The suction was measured approximately 1 m above ground surface and applied to the wellpoint screen 5 m to 6 m below ground surface. This accounts for an elevation loss of 6 m (60 kPa) to the top of the wellpoint screen. Other losses in suction through the system such as friction and leakages were not determined. The elevation, friction, and leakage losses result in a reduction of the measured pump suction to the estimated applied suction at the wellpoint screen. A range of applied suction from 10 kPa to 60 kPa were considered for the modelling calibration.

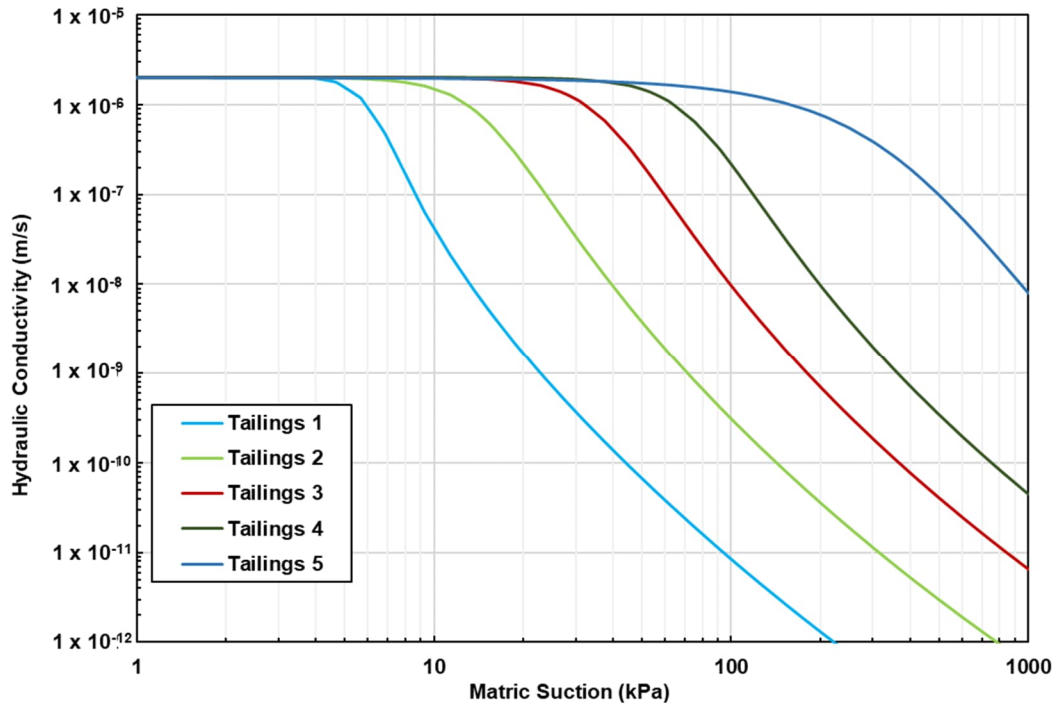


Figure 14: Range of Hydraulic Conductivity Functions used in Model Calibration

Model Calibration Results

Tailings properties that provided the best fit to field data for individual wellpoint sections are presented in Table 3. The best fit results provide a baseline set of parameters to evaluate the full cross section and to create a calibrated model. Both the SWCC and saturated horizontal hydraulic conductivities that provided best fit to the field data of individual wellpoint section are representative of coarse tailings. The best fit saturated horizontal hydraulic conductivities vary in a narrow range from 9×10^{-7} m/s for Scenario 3, to 2×10^{-6} m/s for Scenario 2, to 6×10^{-6} m/s for Scenario 1. The hydraulic conductivity ratios vary from 0.05 to 0.1. The variability of the resulting tailings properties may be related to the change in content of coarse tailings and fine tailings in the wellpoint sections and assumptions made to develop the models.

The three sets of best fit parameters obtained from Scenario 1 through 3 were used and evaluated for the entire cross-section (i.e., Scenario 4). A comparison of flow rate results is presented in Table 4. The flow rates are compared to Day 25 of dewatering operation. Day 25 was selected as a comparison date when the observed hydraulic head responses were at maximum drawdown and flow rates had stabilized. Some measured piezometric elevations in the last few days of the dewatering trial operation were affected by the loading of construction equipment.

Table 3: Best Fit Tailings Properties for Scenarios 1 To 3

Scenario	Zone	Wellpoint Section	Tailings Properties		
			SWCC	k_h (m/ s)	k_v/ k_h
1	D	6	Tailings 2	6×10^{-6}	0.05
2	B	2	Tailings 2	2×10^{-6}	0.08
3	B, D	4	Tailings 2	9×10^{-7}	0.10

Table 4: Comparison of observed and modelled flow rates

Best fit Parameters from	Modelled Flow Rate per m at Day 25 (L/ min)			Comparison to Measured Flow Rate per m at Day 25		
	Section 6	Section 4	Section 2	Section 6	Section 4	Section 2
Scenario 1	0.40	0.27	0.36	88%	333%	178%
Scenario 2	0.20	0.15	0.18	45%	192%	92%
Scenario 3	0.11	0.09	0.10	24%	110%	51%

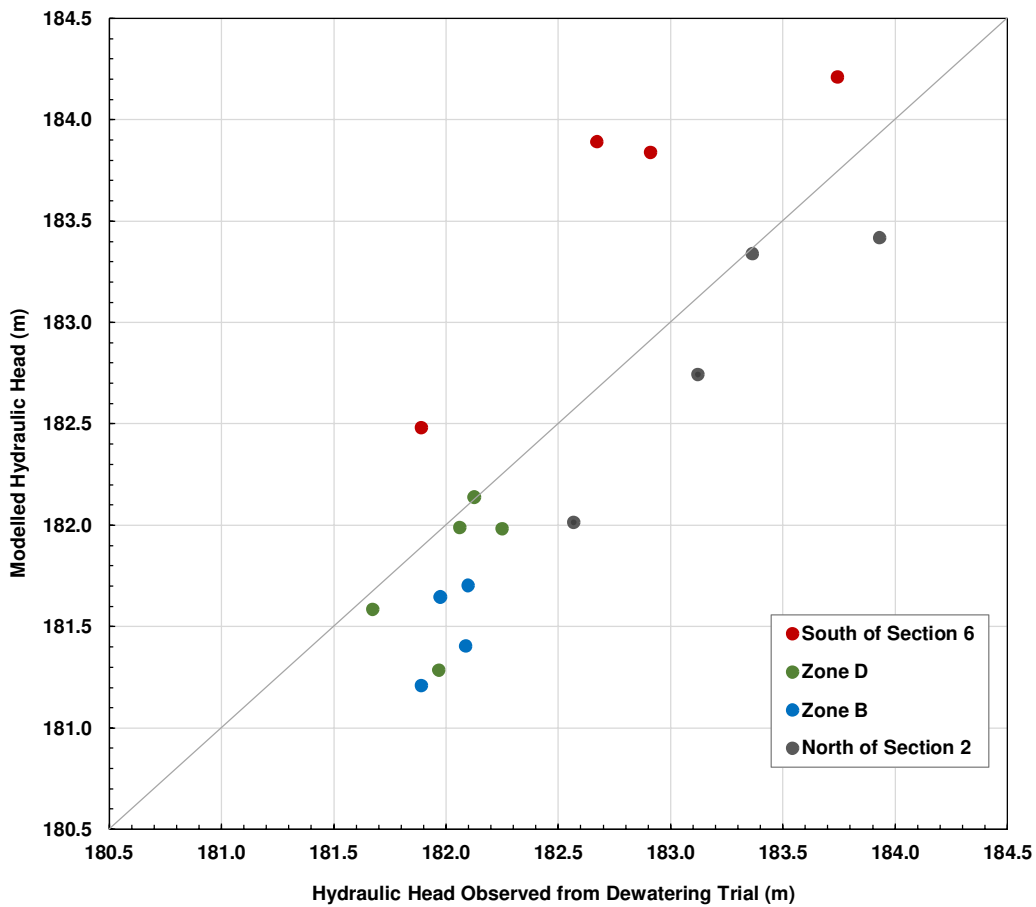


Figure 15: Comparison of observed and modelled hydraulic head at day 25

Based on the results of the analysis, the best fit parameters from Scenario 2, with the SWCC for Tailings 2, k_h of 2×10^{-6} m/ s and k_v/k_h of 0.08 would provide representative tailings properties for the tailings between the wellpoint rows. These parameters can be considered a best representation of the bulk properties of the tailings in the South Pond based on flow rate and hydraulic head observations of the dewatering trial. Figure 15 presents the comparison of the modelled and observed hydraulic heads from the piezometers on day 25 of the dewatering trial. The data have been separated by zone / area to geographically differentiate locations.

Simulation of Recovering Period

The calibrated model was applied past the active dewatering period to assess the recovery process, comparing the modelled and observed hydraulic head during the recovery. The modelling was extended 57 days to 6 December 2022, on which the last data were collected in 2022. Following 28 days of dewatering the constant pressure head boundary condition applied to the wellpoint sections was removed. Figure 16 presents the comparison plots of modelled and observed hydraulic head for VWP35, SP2 and VW36, located in Zone B. Figure 17 presents the comparison plots of modelled and observed hydraulic head for piezometers VW37 to VW42, located in Zone D. The modelled hydraulic head generally matches the measured hydraulic head for the recovery, but with the variations related to the monitoring locations. Over the range of monitoring locations, it can be observed that the modelled hydraulic heads are underestimated in the south, transitioning to overestimated in the centre, and back to being a close match in the North.

It should be noted that regrading of the dewatering trial area started on 20 October 2022, which created an observed pressure spike in many of the monitoring locations. It can be observed that the trend of the measured hydraulic head is generally decreasing for the last 30 days of the plots. This may indicate that the groundwater table is generally decreasing in the South Pond. It should be noted that seasonal variation of groundwater table in the South Pond was not included in the model.

Parametric Study

The calibrated model was used to conduct a parametric study of the parameters used in the model, to evaluate the effect of input parameters on the water volumes captured at the wellpoint sections during the dewatering operation (i.e., for 28 days). Table 5 presents the parameters and the range of values that were considered in the parametric study. During the parametric analysis, one parameter was changed at a time to evaluate the effect it has on the flow rates of each of the wellpoint sections. Parameters that provided best fit to the field data were selected for the base case.

Table 6 presents the results of parametric study for wellpoint Section 2. Considering the range of input values shown in Table 5, the results indicate that horizontal hydraulic conductivity of tailings has the most significant effect on the extracted water volumes, from 14% to 548% of base case volume. Hydraulic conductivity ratio would have next significant effect, from 28% to 154% of base case volume.

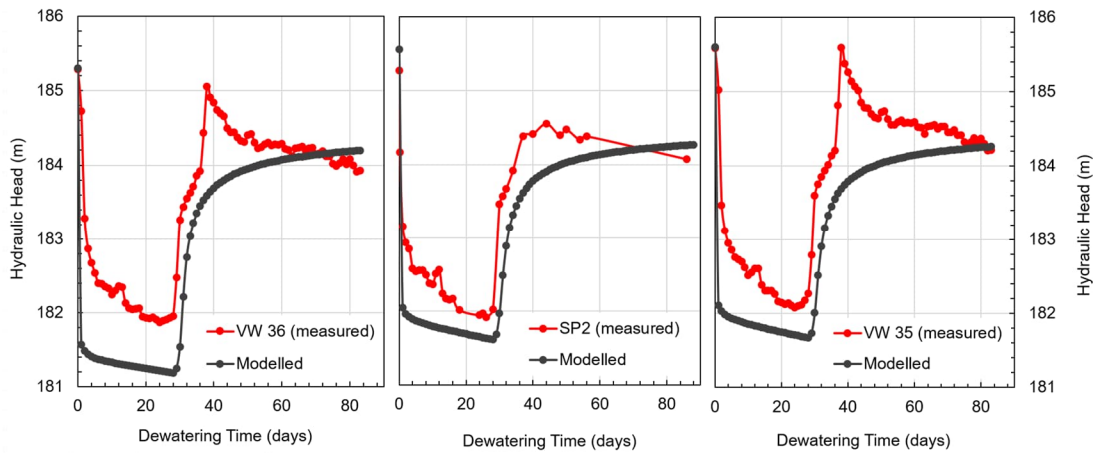


Figure 16: Comparison of Modelled and Measured Hydraulic Head for Zone B (Wellpoint Sections 2 and 4)

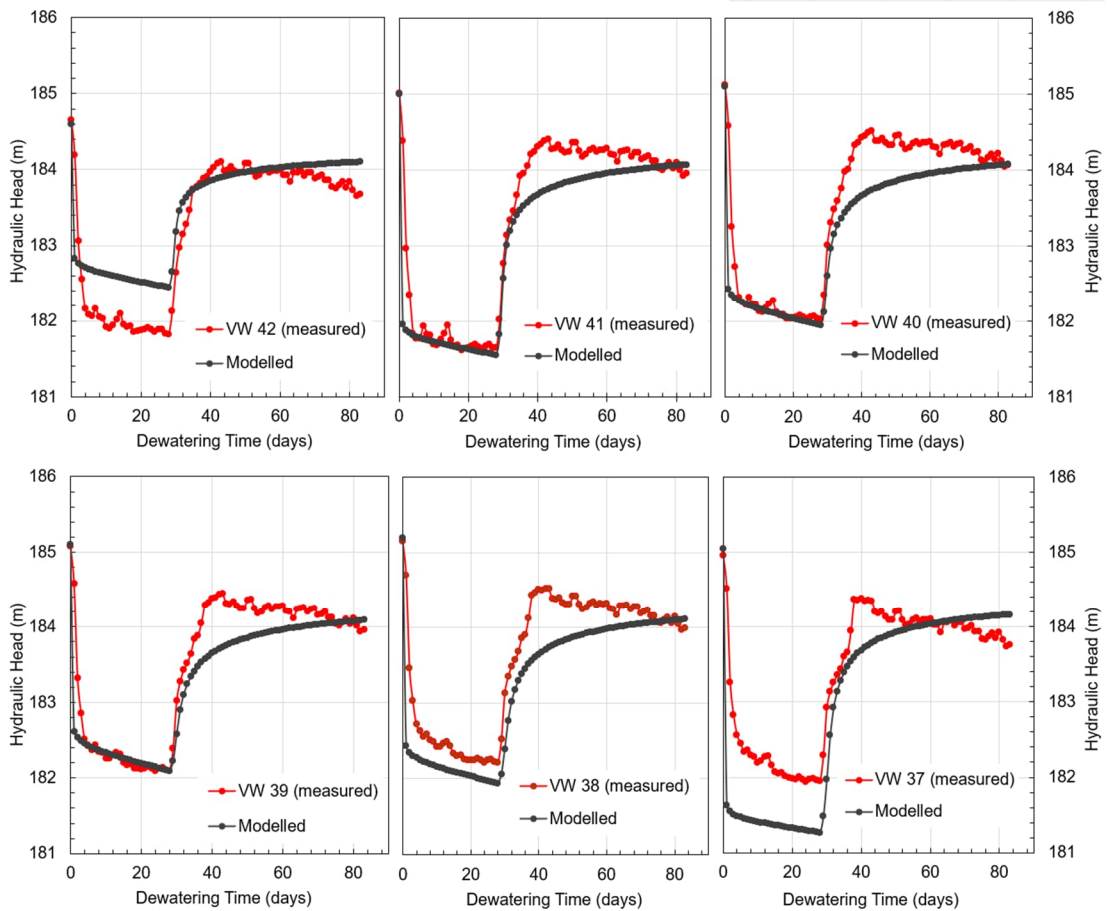


Figure 17: Comparison of Modelled and Measured Hydraulic Head for Zone D (Wellpoint Sections 4 and 6)

Table 5: Parameters and Range of Values Used for Parametric Study

Parameter	Low	Base Case	High
SWCC	Tailings 1	Tailings 2	Tailings 5
Horizontal saturated hydraulic conductivity, k_h (m/ s)	2×10^{-7}	2×10^{-6}	2×10^{-5}
Hydraulic conductivity ratio, k_v/ k_h	0.01	0.08	0.2
Applied suction (kPa)	10	40	60

Assessment of Dewatering Effectiveness

This section presents an assessment of the dewatering effectiveness in lowering tailings water content to support tailings excavation, transportation, and placement. The vacuum enhanced method could be used to lower water table to approximately 6 m with various wellpoint row spacings. However, for illustration purpose, groundwater, and wellpoint configuration similar to those from the dewatering trial were used for the assessment in this study. These conditions consider two different wellpoint row spacings (i.e., 30 m wellpoint row spacing and 15 m wellpoint row spacing), and 3 m to 4 m thick layer of saturated tailings. It is assumed that wellpoints in a row are closely spaced (1.5 m to 2.5 m) to create two-dimensional conditions between wellpoint rows. The assessment is based on the numerical modelling results by using the calibrated tailings hydraulic properties. The calibrated tailings hydraulic properties were obtained from dewatering of the field trial. A transient numerical modelling was used to assess the following changes in tailings with dewatering time. A dewatering time of up to 90 days was considered.

- extraction groundwater volumes
- pore-water pressures (dewatering depth)
- changes in tailings water contents

Table 6: Results of Parametric Study for Section 2

Parameter	Measured from Section 2 (m^3/ m)	Modelled Cumulative Volume (m^3/ m) During 28 Days of Dewatering			Percent of Base Case Flow Volume		
		Low	Base Case	High	Measured from Section 2	Low from Parametric Study	High from Parametric Study
		(1)	(2)	(3)	(4)	(1)/ (3)	(2)/ (3)
SWCC	7.1	6.8	8.1	9.5	88%	84%	117%
Horizontal saturated hydraulic conductivity, k_h (m/ s)	7.1	1.1	8.1	44.4	88%	14%	548%
Hydraulic conductivity ratio, k_v/ k_h	7.1	3.5	8.1	12.5	88%	43%	154%
Applied suction (kPa)	7.1	7	8.1	8.1	88%	86%	100%

Water content in soils is often described by volumetric water content (VWC), gravimetric water content (w) and degree of saturation (S). Volumetric water content was used for the numerical analysis; however, degree of saturation indicates the workable condition of the tailings, and gravimetric water content indicates the dry density of the materials can be achieved through compaction.

Figures 18 and 19 present the degree of saturation profiles at the middle of the wellpoint row spacing at select times for 30 m and 15 m wellpoint row spacings, respectively. The modelled average degrees of saturation in the unsaturated tailings due to dewatering in the 15 m wellpoint row spacing are similar to those in the 30 m wellpoint row spacing; however, the resulting unsaturated tailings thickness in the 15 m wellpoint row spacing (approximately 4.5 m) is larger than in the 30 m wellpoint row spacing (approximately 3 m). Table 7 presents a comparison of the estimated dry density, gravimetric water content, and degree of saturation prior to dewatering, after 30 days and 60 days of dewatering, and after excavation following 60 days of dewatering. Table 7 shows the unsaturated tailings in the 15 m wellpoint row spacing have slightly lower degree of saturation and gravimetric water content after 60 days of dewatering and followed excavation than for dewatering in the 30 m wellpoint row spacing. Again, the tailings at this state would be suitable for excavation and handling (i.e., transportation) but would require further drying to allow compaction.

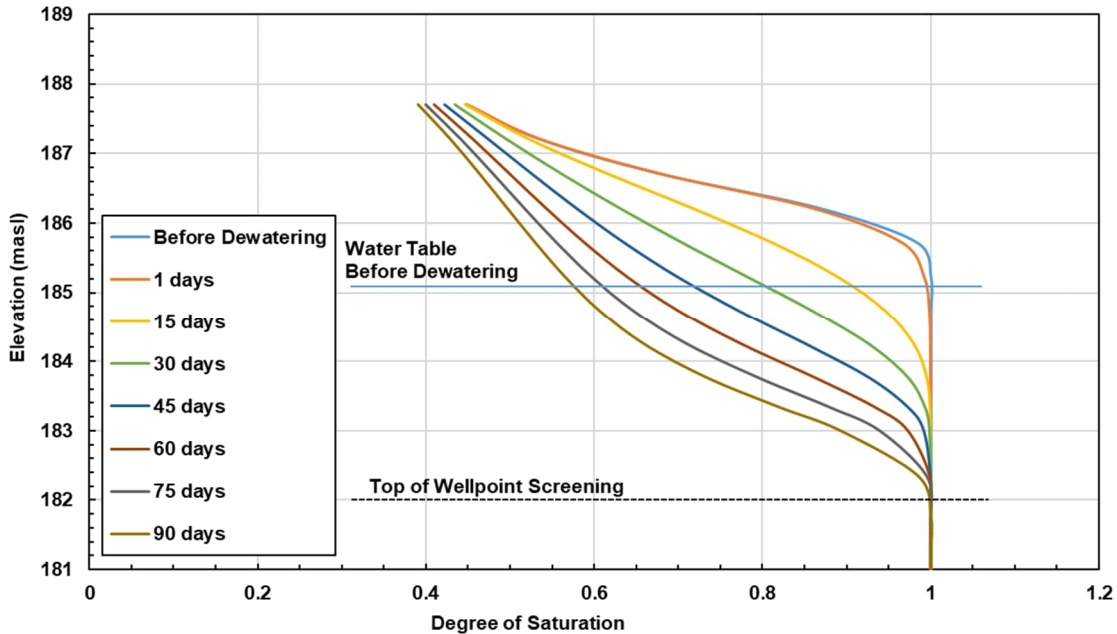


Figure 18: Degree of saturation profiles at select times – 30 m wellpoint row spacing

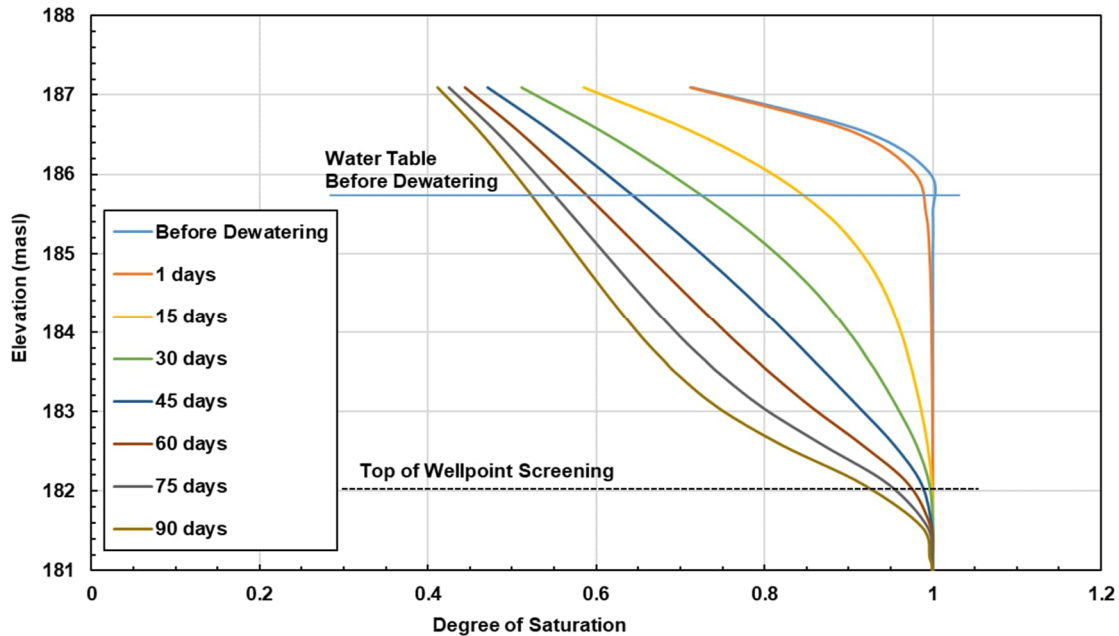


Figure 19: Degree of saturation profiles at select times – 15 m wellpoint row spacing

Table 7: Comparison of Tailings States along Dewatering and Excavation for 30 m and 15 m Wellpoint Row Spacing

Dewatering Condition	Parameter	30 m Wellpoint Row Spacing	15 m Wellpoint Row Spacing
Prior to dewatering	Degree of Saturation (%)	100	100
	Gravimetric Water Content (%)	27.6	27.6
	Dry Density (kg/ m ³)	1,596	1,596
After 30 days dewatering	Degree of Saturation (%)	94	93
	Gravimetric Water Content (%)	26.0	25.6
	Dry Density (kg/ m ³)	1,596	1,596
After 60 days dewatering	Degree of Saturation (%)	86	84
	Gravimetric Water Content (%)	23.7	23.2
	Dry Density (kg/ m ³)	1,596	1,596
After excavation following 60 days dewatering	Degree of Saturation (%)	70	68
	Gravimetric Water Content (%)	23.7	23.2
	Dry Density (kg/ m ³)	1,450	1,450

Change in Tailings Volume Mass Properties

The volume-mass properties of tailings (i.e., tailings condition) were estimated after dewatering to assess feasibility of tailings placement. The assessment of tailings condition after dewatering focuses on gravimetric water content and dry density, which links to the proctor

compaction results for the tailings. Figure 20 presents the estimated dry density and gravimetric water content for the tailings in the unsaturated zone, developed due to dewatering for the 30 m wellpoint row spacing. The modelled average degrees of saturation within the tailings are used to calculate gravimetric water content of the tailings. Tailings dry density would be unchanged for the tailings in place (i.e., prior to excavation). Tailings consolidation would occur during dewatering but is considered negligible due to a short period of dewatering. A bulking factor of 10% is assumed for tailings volume loosening due to excavation followed 60 days of dewatering to estimate dry density after excavation.

The estimated dry density for the tailings in place is approximately 1,596 kg/m³ as shown for the points of before dewatering, 30 days dewatering and 60 days dewatering in Figure 20. This dry density accounts for about 92% of the maximum dry density obtained from standard proctor compaction test for the combined fine and coarse tailings. The excavated tailings would have a dry density of 1,450 kg/m³ after volume expansion (assumed 10% swelling). The estimated tailings gravimetric water content is about 27.6% prior to dewatering, which is close to the average water content measured for the tailings samples before trial. The tailings water content reduces to approximately 26.0% after 30 days of dewatering and 23.7% after 60 days of dewatering. Correspondingly, the degree of saturation in the tailings may reduce from 100% prior to dewatering to near 94% after 30 days of dewatering and 86% after 60 days of dewatering. Figure 20 shows that, after 60 days of dewatering, the degree of saturation for the tailings in place would achieve approximately 85%. If the tailings were excavated after 60 days of dewatering, the excavated tailings would have approximately 70% degree of saturation. The water content of the excavated tailing is approximately 5% over optimum water content. The tailings at this saturation and water content would be suitable for excavation and handling (i.e., transportation) but would require some drying to allow compaction. The excavated tailings would need to be conditioned (e.g., drying or mixing with dryer tailings) to achieve a gravimetric water content of 2% to 3% over the optimum water content for compaction, and assumed to be compacted to around 92% of the maximum dry density.

Summary

Vacuum enhanced dewatering is expected to be an effective first step to allow excavation and hauling of the South Pond tailings. The modelling was completed assuming hydraulic properties of bulk tailings, which reflect the tailings as a whole. It is expected that fine zones in the tailings will be dewatered to a lesser degree and will need to be conditioned prior to compaction. Further drying and mixing with dryer tailings will be required for placement and compaction.

The dewatering trial field data and modelling work completed in this study indicate that vacuum enhanced method could be used to dewater saturated tailings in the South Pond. The effect of dewatering to lower the groundwater table was demonstrated by hydraulic head responses observed in the field trial, by test pitting experience, and verified by numerical analysis.

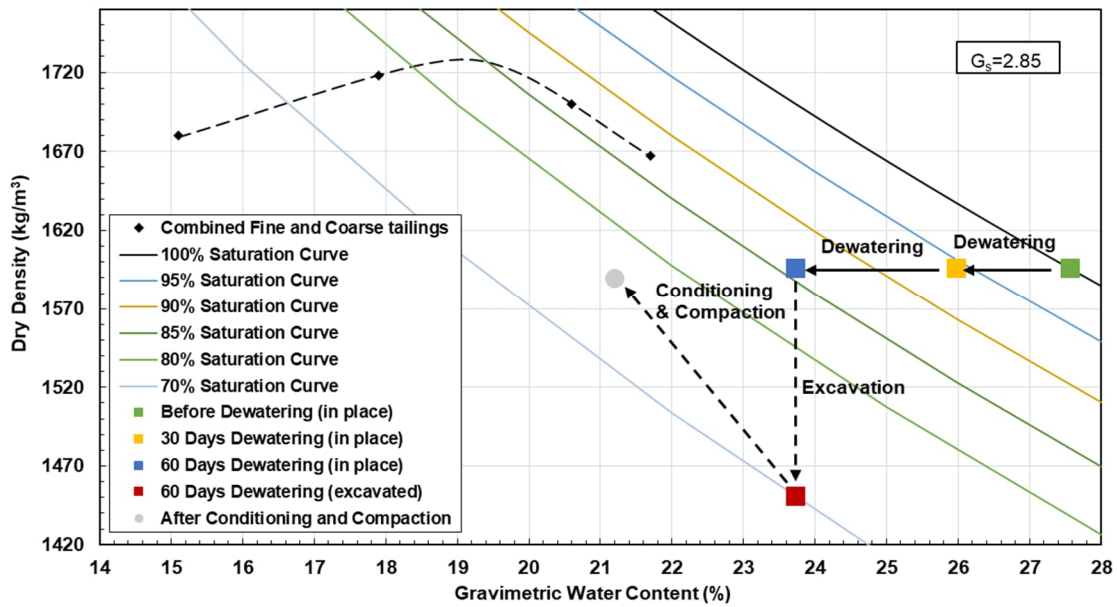


Figure 20: Estimated tailings dry density and gravimetric water content with dewatering and excavation – 30 m well point row spacing

The dewatering trial was observed to be effective in lowering the groundwater table in both the 15 m and 30 m spacings. Through numerical analysis, it was demonstrated that the 15 m spacing is expected to achieve a measurable improvement on the dewatering of the tailings. These effects can be offset with a wider spacing and a longer dewatering time.

Through numerical analysis, a significant amount of groundwater drawdown and reduction in tailings degree of saturation was demonstrated if dewatering period is extended to two or three months, however this was not confirmed through sampling and lab testing from the field program. It should be noted that the analysis presented in this study assumed no recharge to the dewatering area during dewatering operation. Dewatered tailings would likely be workable and suitable for excavation and handling.

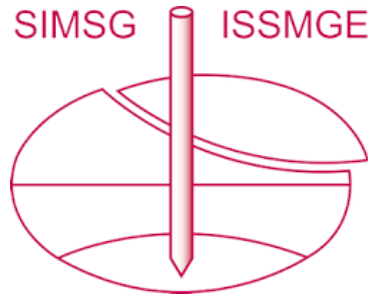
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