Wick Drain Design and Construction in Soft Clay Foundation of a Tailings Dam

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ABSTRACT
A thick normally consolidated glaciolacustrine clay layer is present below the foundation of an existing tailings dam. Enhanced drainage measures will be required for future raises of the dam to manage pore pressure conditions in the clay layer during subsequent staged fill placement. Prefabricated vertical drains (wick drains) were installed in July 2021 in the dam downstream foundation to promote dissipation of the excess pore water pressure in the layer due to the current and future dam fill placement. This paper summarizes the key design and construction considerations of the wick drains. Numerical consolidation modeling was used in the design of the wick drains to simulate various design and sensitivity cases. As a part of the design process, calibration consolidation modelling was also conducted to estimate the coefficient of consolidation of the clay based on historic pore water pressure data measured at the site. Recent pore water pressure readings measured in the clay after the wick drain installation are also presented to show the actual wick drain performance. Numerical consolidation back-analyses were conducted to match the measured piezometric data at a piezometer installed in the wick drain area.

RÉSUMÉ
Une épaisse couche d'argile glaciolacustre normalement consolidée est présente sous la fondation d'un barrage à résidus existant. Des mesures de drainage améliorées seront nécessaires pour les futures montées du barrage afin de gérer les conditions de pression interstitielle dans la couche d'argile lors de la mise en place ultérieure du remblai par étapes. Des drains verticaux préfabriqués (drains à mèche) ont été installés en juillet 2021 dans la fondation en aval du barrage pour favoriser la dissipation de l'excès de pression d'eau interstitielle dans la couche en raison de la mise en place actuelle et future du remblai du barrage. Cet article résume les principales considérations de conception et de construction des drains à mèche. La modélisation numérique de la consolidation a été utilisée dans la conception des drains à mèche pour modéliser divers cas de conception et de sensibilité. Dans le cadre du processus de conception, une modélisation de la consolidation de l'étalonnage a également été réalisée pour estimer le coefficient de consolidation de l'argile sur la base des données historiques de pression interstitielle mesurées sur le site. Des lectures récentes de pression interstitielle mesurées dans l'argile après l'installation du drain à mèche sont également présentées pour montrer les performances réelles du drain à mèche. Des analyses numériques de consolidation ont été effectuées pour faire correspondre les données piézométriques mesurées à un piézomètre installé dans la zone du drain à mèche.

1 INTRODUCTION

Evolution Mining Red Lake Operation (RLO) is an underground gold mine, located in Balmertown, Ontario about 6 km east of Red Lake. Splitter Dyke 1 (SD1) is one of the tailings dams for Tailings Area 1 (TA1) of the mine. Figure 1 shows the relative location plan of TA1 and SD1 in an orthophoto (May 2021) of the site.

A downstream waste rock buttress of SD1 was designed to meet stability requirements for a proposed raise of TA1 structures to El. 375 m. Enhanced drainage measures (i.e. wick drains) were not necessary for the proposed raise configuration to El. 375 m, as the designed buttress for SD1 was adequate to mitigate the excess pore pressures generated in the foundation glaciolacustrine clays during construction.

As part of future development, SD1 is likely to be raised. Tailings management planning is currently in process to assess the potential raise schedule for SD1. Enhanced drainage measures will likely be required for future raises (beyond El. 375 m) of SD1 to manage pore pressure generation in the clays during subsequent staged fill placement. It was recognized that it will become more challenging and costly to install wick drains in the foundation as the depth of the downstream waste rock buttress increases. To avoid future difficulty with installing the drains through a thicker waste rock buttress, and in order to provide flexibility for design of future raises, in early 2021, RLO installed wick drains after the first lift of waste rock was placed within the buttress area.

RLO retained Wood Environment & Infrastructure Solutions Canada Limited (Wood) to complete an

assessment for the wick drain spacing and develop the wick drain design. This paper summarizes the assessment basis and presents the wick drain design as well as an overview of construction. Recent pore water pressure readings measured in the clay after the wick drain installation are also presented to show the actual wick drain performance. Numerical consolidation analyses were conducted to match the measured piezometric data at a piezometer installed in the wick drain area.

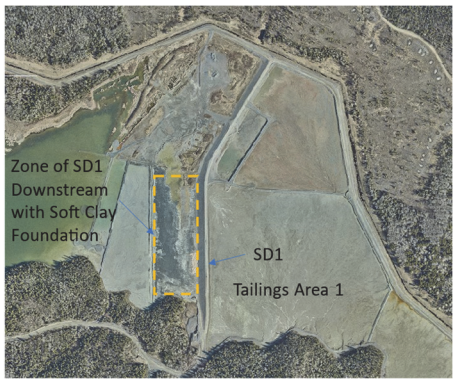


Figure 1. Relative location plan of TA1 and SD1

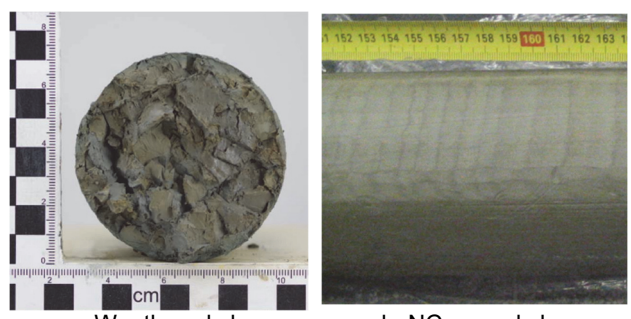
2 BACKGROUND AND DAM FOUNDATION CONDITIONS

A deposit (up to 12.5 m) of varved glaciolacustrine clay underlies much of the foundation of SD1. As well, there are zones of potentially liquefiable materials in the foundation of SD1 (the historical tailings). These two units controlled the stability of the containment structures in previous designs. Preliminary long-term tailings management planning indicates that future SD1 raises to higher crest elevations may be required. The estimated time between the raises is about 2 to 3 years based on the proposed future mine production plan. The rates of the SD1 rise would be faster than that for historical raises, and therefore leave less time for natural dissipation of the excess pore water pressures generated in the clay layers due to future fill placement. Installation of wick drains in the clay layers will increase the dissipation rate of the excess pore water pressures and the rate of strength gain due to primary consolidation of the soft clay soils.

Prefabricated vertical drains or wick drains are drainage strips that comprise a flat core within a filter jacket. Such prefabricated drains are manufactured from polymeric materials, with a semirigid core that is typically 100 mm wide and 2 mm to 4 mm thick. The filter jacket is a geotextile, in many cases a heat-bonded, nonwoven fabric that is typically 0.5 mm thick. The function of the core is to provide a series of flow paths along the length of the drain, and the function of the filter is to prevent soil particles from entering the core and contaminating those flow paths. Wick drains are used to shorten the drainage path length, by preferential radial seepage to the vertical drains, with the intention of accelerating the rate of primary consolidation (Crawford et al. 1992).

The most common form of wick drain installation is a displacement method utilizing a steel mandrel to force its way into the soft soils and make room for the strip drain. It is common practice to use an anchor at the bottom tip of the wick drain to hold the wick drain in place when the mandrel is withdrawn. This installation process causes disturbance and remolding of the clay in the immediate vicinity of the mandrel and anchor, thereby reducing the permeability of the soil in an area surrounding the drain. This problem, known as the 'smear effect', reduces the rate of infiltration of the dissipating excess pore water into the wick drain (Dittrich et al. 2010).

Dam foundation soils within the SD1 footprint consist of historical deposits of tailings, underlain by peat, glaciolacustrine medium to high plastic clay, silt and sand, and glacial till. The glaciolacustrine silty clays occur in low lying areas, are varved in nature, with an upper weathered, desiccated crust transitioning to normally consolidated (NC) with depth. Fissuring in the weathered clay results in a nuggety structure (Figure 2a) which decreases with depth. From undisturbed Shelby tube samples, the darker clay varves were observed to be generally a few millimeters thick, with the lighter, siltier varves ranging from about 5 to 20 mm thick (Figure 2b). Atterberg limits were performed on the dark- and light-colored layers separately in a past testing program. The dark grey layers were classified as clays of high plasticity (CH) and the light grey varves are classified as medium plasticity (silty) clay (CI). Interbedded layers of sands and silts were randomly encountered below the clay. The silt and sand deposit occur as irregular glaciofluvial deposits within the glacial till unit. The glacial till is a dense sandy silt overlying bedrock.



a. Weathered clay b. NC varved clay

Figure 2. Photos of weathered clay and NC varved clay

3 ANALYSIS METHODOLOGY AND VERIFICATION

SIGMA/W (version 8.16.5.15361) is a finite element software product that was developed by GEO-SLOPE International Ltd. (now Seequent, and Bentley). It can be used to perform stress and deformation analyses of earth structures. SIGMA/W is also formulated to solve soil consolidation problems using a fully coupled or any of several uncoupled options. It can simulate the generation of excess pore pressure in clays upon loading and then predict the dissipation of the excess pore pressure with time after the loading. This software was used in this study to predict excess pore pressure dissipation in the SD1

foundation clays for various cases without and with wick drains after the SD1 downstream buttress is placed.

A consolidation analysis using SIGMA/W for a simple example was conducted to verify the software capability and compare with analytical solution results. The modelled results exactly matched the analytical solution (Terzaghi's one-dimensional consolidation theory), suggesting that the SIGMA/W model can be used for consolidation simulation.

4 CLAY PROPERTIES

4.1 Geotechnical Parameters of Clay

Table 1 summarizes some of geotechnical parameters of the glaciolacustrine clay. The consolidation parameters were determined from laboratory 1-D consolidation tests on piston samples of the clay in the SD1 area. The peak undrained shear strength and sensitivity (ratio of undisturbed shear strength over remolded shear strength) values were based on in-situ Nilcon field vane testing in several test holes downstream of SD1.

Table 1. Geotechnical parameters of glaciolacustrine clay

Parameter	Value
Thickness of clay	up to 12.5 m
Liquid limit	21% to 69%
Plastic limit	14% to 29%
Plasticity index	7% to 40%
Compression index	0.2 to 0.8
Coefficient of consolidation	1.6E-4 to 7.0E-2 cm^2/s
Estimated over-consolidation ratio (OCR)	2 to 5 (weathered clay) 1 to 2 (NC clay)
Undrained shear strength	4 to 29 kPa (NC clay)
Sensitivity	1.2 to 2.1 (NC clay)

4.2 Coefficient of Vertical Consolidation

Given the importance of the coefficient of vertical consolidation, C_v, for the consolidation analyses, both an assessment of laboratory consolidation testing data and an assessment of available pore pressure dissipation data in the clays (from previous loading) were carried out to establish the appropriate range of C_v to be used in the consolidation analyses.

The values of C_v were estimated using available piezometric data from previous raises (loading) and subsequent measured pore pressure dissipation readings. Calibration consolidation analyses were completed using the SIGMA/W model, with actual clay thicknesses and drainage boundary conditions. Calibration consolidation analyses were carried out to estimate the values of C_v for the normally consolidated clay layer by obtaining a close match with the measured historical piezometric data at four piezometers (SD1-PZ11-03, SD1-PZ11-04, ND-PZ04-12, and ND-PZ04-15). These four piezometers were installed in the normally consolidated clay layer and have consistent records of measured data and past loading conditions. ND-PZ04-12 and ND-PZ04-15 were installed inside or close to a wick drain area installed in 1999 at a nearby site. The wick drains were installed at a spacing of 3 m in a square pattern. SD1-PZ11-03 and SD1-PZ11-04 were installed through the SD1 crest in the SD1 foundation without wick drains.

Laboratory one-dimensional consolidation tests were also completed on undisturbed samples of the glaciolacustrine clays collected during various past site investigations. Figure 3 shows the C_v values for the clay samples for a vertical effective stress range of 100 kPa to 400 kPa. The average value of C_v is 1.1E-3 cm^2/s for all data in the figure. This value was selected as a reasonably upper value of C_v for the SD1 wick drain assessment and design in this study.

The ranges of C_v values from the calibration analyses for the four piezometer locations were also presented in Figure 3. They generally fall in the similar range of the laboratory data but with a trend towards the lower end. A line of C_v of 4.0E-4 cm^2/s is shown in Figure 3 to represent a reasonably lower C_v that was selected as a lower value for the SD1 wick drain assessment and design.

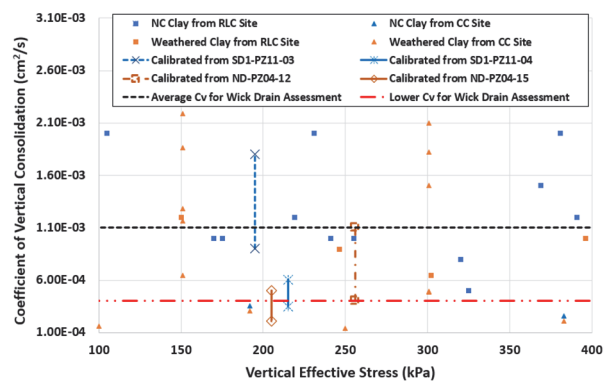


Figure 3. C_v values of clay sample laboratory consolidation tests and those from the calibration analyses

5 SD1 WICK DRAIN ASSESSMENT

5.1 Assessment Methodology

SIGMA/W was used in the wick drain assessment to simulate the generation of excess pore pressure in clays upon loading and then predict the dissipation of the excess pore pressure with time after the loading. An axisymmetric model was adopted to simulate an equivalent cylinder of clays with a wick drain at the center and a smear zone immediately outside the wick drain.

Available measured piezometric data at the mine site indicated that hydrostatic conditions were present in the soil layers above the top of the clay layers and below the bottom of the clay layers. Those foundation soils are more permeable than the clay layers; therefore, both the top and bottom of the clay layers were assigned as a free drainage boundary condition. A linear elastic (with pore water pressure change) material model for the clay was used in the consolidation analyses. This model is simple to obtain converged solutions compared with more complicated models such as Modified Cam Clay model. For the current

wick drain spacing assessment that focused on prediction of excess pore water dissipation with time (other than prediction of consolidation induced ground settlement), the linear elastic model was considered to be reasonable and adequate.

Parametric sensitivity analyses were also conducted to evaluate the sensitivity of the results to selected key input parameters.

5.2 Key Analysis Parameters

A typical wick drain dimension of 102 mm by 2 mm was selected. Calculated using an equation recommended in FHWA (1986), an equivalent diameter of 0.052 m for a wick drain was used in the assessment.

The discharge capacity of a wick drain is typically provided by wick drain manufactures. The discharge capacity of wick drains (as measured according to ASTM D4716) is about 6 to 9 liters per minute. Tran Nguyen et al. (2010) investigated the discharge capacity behavior of deformed wick drains using a laboratory performance test. It was found that the reduction of the discharge capacity of the tested wick drains varied with the type of wick drains and percentage settlement. Reduction of discharge capacity reached 40% to 80% at a percentage settlement of 30% for three core shapes (continuous channel, grooved and monofilament). For this assessment, the equivalent hydraulic conductivity of the wick drain was assumed to be 0.01 m/s, which is equivalent to a discharge capacity of 1.2 liters per minute or 20% of the typical discharge capacity values from wick drain manufactures. Sensitivity analyses indicated that the equivalent hydraulic conductivity of the wick drain had no or little effect on the consolidation results until it is lower than 0.0001 m/s. As noted in Hansbo (1997), the discharge capacity of modern band drain types is generally high enough for well resistance (or wick drain core vertical hydraulic resistance) to be neglected, even in cases where the drains have been installed to great depths.

A smear zone or disturbance zone due to pushing the mandrel (and anchor if used) into the clay during wick drain installation is expected to form between the wick drain and the native clays. The dimensions and properties of this smear zone will depend on several factors such as the mandrel (as well as anchor if used) size and shape, soil microfabric (soil layering), and installation procedure. Dittrich et al. (2010) reviewed ten sources in literature, including studies, laboratory tests, numerical analysis, and back analysis, and summarized the equivalent diameter of the smear zone (d_s), which is about 1.6 to 5 (with an average value of 3) times of the equivalent diameter of the mandrel (d_m). For this assessment, we assumed that the equivalent d_s is equal to 3 times of the equivalent d_m. A sensitivity analysis was conducted to evaluate a case with d_s to be equal to 5 times of the equivalent d_m.

The 'smear ratio' is defined as the ratio of the horizontal permeability of the undisturbed soils (beyond the smear zone) to the permeability of the soil within the disturbed zone or smear zone (k_h/k_s) (Dittrich et al. 2010). It is generally accepted that the value of the smear ratio is a difficult parameter to estimate for wick drain design. Some researchers have carried out studies, in an attempt, to estimate the value of smear ratio for a particular site or type of clay. These studies have typically been based on back analysis from field monitoring data, although some are based on large scale laboratory testing. The estimated values of permeability (or smear) ratio from several of these studies are summarized in Dittrich et al. (2010). For the sites and/or types of clay soils investigated, the smear ratio (k_h/k_s) ranged from as low as about 1 to as high as 10. The average of the above range of data is about 4. In the current assessment, we assumed that the smear ratio (k_h/k_s) was 4 for the base cases. Sensitivity analyses were also conducted for the ratios of 10 and 20 for a selected case.

The time to achieve a given percent consolidation is a function of the square of the diameter of the influence cylinder (D). D is a controllable variable since it is a function of drain spacing only. Vertical drains are commonly installed in square or triangular patterns. For this assessment, the wick drains have a square pattern; in this case, the diameter of the influence cylinder is equal to 1.128 times of the wick drain spacing (Craig 2004).

The measurements of coefficient of horizontal consolidation are not available for the RLO site. The coefficient of horizontal consolidation, C_h, can be estimated using the equation of $C_h = (k_h/k_v)*C_v$. The typical value of k_h/k_v for soft clays ranges from 1 to 10 (FHWA 1986). For this assessment, it was conservatively assumed that the k_h/k_v is 2 for the clay layers (given that these are varved clays, for which k_h/k_v of 10 is possible). If the actual ratio is higher, the clay consolidation will be faster than the predicted. Sensitivity analyses were also conducted for the ratios of 5 and 10 for a selected case. The vertical hydraulic conductivity (k_v) of the clays varied from 1.0E-8 cm/s to 8.0E-8 cm/s for a vertical effective stress range of 100 to 400 kPa in the laboratory consolidation tests on the clay samples from the RLO site. A value of 5.0E-8 cm/s was adopted in this assessment. This value does not directly affect the consolidation analysis results since it is indirectly included in the coefficient of vertical consolidation (C_v), which is the key parameter affecting the clay consolidation.

Two C_v values for the clay layers were used in this assessment: 1.1E-3 cm^2/s (average value) and 4.0E-4 cm^2/s (lower value), as discussed in Section 4.2 above.

The initial excess pore water pressures in the clay layers upon surface loading (simulating waste rock fill placement for SD1 buttress construction) were generated based on a B-bar pore water coefficient of 1.0. This value may be conservative for the over-consolidated weathered clay if the maximum effective vertical stress after consolidation is no greater than the pre-consolidation effective vertical stress. The total surface vertical loads with time were applied in the consolidation analyses. The loads are approximately equivalent to 0.5 m thick waste rock placement in each 15-day period, for a total of 3 m thick waste rock within 3 months.

5.3 Assessment Cases

Table 2 lists the base cases evaluated in the wick drain consolidation assessment.

Table 2. Bases cases in wick drain assessment

Cases	Clay Thickness (m)	C_v of Clay (cm^2/s)	Wick Drain Spacing (m)
A1	12.5	1.1E-3	No wick drain
A2	12.5	1.1E-3	2.5
A3	12.5	1.1E-3	2.0
A4	12.5	1.1E-3	1.5
A5	7.0	1.1E-3	2.5
A6	7.0	1.1E-3	2.0
A7	4.5	1.1E-3	No wick drain
B1	12.5	4.0E-04	No wick drain
B2	12.5	4.0E-04	2.5
B3	12.5	4.0E-04	2.0
B4	12.5	4.0E-04	1.5
B5	7.0	4.0E-04	2.5
B6	7.0	4.0E-04	2.0
B7	4.5	4.0E-04	No wick drain
B8	4.5	4.0E-04	2.5
B9	4.5	4.0E-04	2.0

Three sensitivity cases (S1 to S3) were also conducted to compare with the results of Case B3:

- S1: same as Case B3 but k_h/k_v of 5 and k_h/k_s of 10
- S2: same as Case B3 but k_h/k_v of 10 and k_h/k_s of 20
- S3: same as Case B3 but assuming d_s/d_m of 5

5.4 Results of Assessment

Figure 4 presents the estimated average consolidation ratio vs. time for Cases B1 to B4.

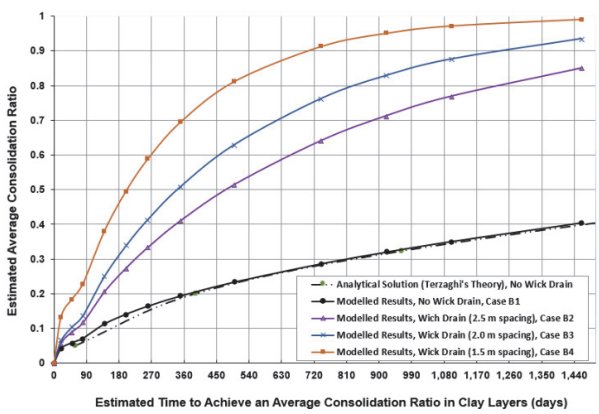


Figure 4. Modelled consolidation results for Cases B1 to B4

The consolidation analysis results indicate the following findings:

- If other parameters/conditions remain the same, the average consolidation ratio for a case with C_v of 4.0E-4 cm2/s is 0.1 to 0.3 lower than that for C_v of 1.1E-3 cm2/s.
- When compared to the cases without wick drains, as expected, the average consolidation ratio increases for cases with wick drains. The increase is greater for a smaller wick drain spacing or for a thicker clay layer if other parameters/conditions remain the same.
- Compared to Case B3, the average consolidation ratios for Cases S1 and S2, which have higher assumed k_h/k_v ratios than Case B3, are slightly (0.01 to 0.04) higher than that for Case B3. This suggests that the consolidation of the clay layers with wick drains is slightly sensitive to the ratio of k_h/k_v. This is because the lateral consolidation with wick drains is heavily affected by the coefficient of consolidation (C_s) of the smear zone, which was assumed to be half of the coefficient of vertical consolidation (C_v) for the clay layers in the assessment.
- The average consolidation ratios for Case S3, which has an assumed larger ratio of d_s/d_m than Case B3, are 0.04 to 0.07 lower than that for Case B3. This suggests that the d_s/d_m ratio assumed has some effects on the estimated consolidation ratio.

6 SD1 DOWNSTREAM WICK DRAIN DESIGN

The target average consolidation ratio in the clay layers is 50% or greater in a year and 75% or greater in two years after the start of waste rock placement, which generates the excess pore water pressure in the clay layers. The target values were selected based on future SD1 raise schedules, preliminary stability analysis results, consolidation analysis results, and engineering judgement. Table 3 summarize the wick drain spacings that meet the target values.

Table 3. Maximum wick drain spacings that meet the target average consolidation ratios

Total Clay Thickness (m)	Wick Drain Spacing (m)	Estimated Average Consolidation Ratio in Clay Layers	
		1 year after start of waste rock placement	2 years after start of waste rock placement
12.5	2.0	0.52 - 0.82	0.75 – 0.97
7.0	2.5	0.53 - 0.82	0.74 – 0.97
4.5	No Wick Drain	0.54 - 0.82	0.75 – 0.97

Table 3 suggests that a wick drain spacing of 2.5 m can be adopted for the area where the total clay thickness ranges from 4.5 m to 7.0 m. The estimated isopach of the total clay thickness in the SD1 downstream area indicates that the area with a clay thickness of 4.5 m to 7.0 m is relatively small and has inclined boundaries. To simplify the wick drain installation, a uniform 2 m spacing (square pattern) is adopted for the selected wick drain area.

The as-designed wick drain area is 120 m wide by 230 m long. Wick drains are not required for the area north of the proposed wick drain area because the total clay thicknesses in the area are relatively thin (0 m to 4.5 m) and where the design consolidation criteria can be met without wick drains.

7 INSTALLATION OF WICK DRAINS

7.1 Overview

Menard Canada of Hamilton, Ontario was retained directly by RLO to complete the installation of the wick drains at SD1. Menard used an OMS wick drain installation machine mounted to a 470 G excavator to complete the installation program. The wick drain machine consisted of sprocket gears, a 23 m high tower equipped with a steel mandrel (used to encase the wick drains), and a high frequency vibro hammer. The installation program was completed between 2 July 2021 and 18 July 2021 and a total 6310 wick drains were installed.

Each wick drain was installed using the displacement method. The steel mandrel was used to force its way through the glaciolacustrine clay until refusal occurred in the underlying sand and till layers, this motion served to make room for the wick drain. An anchor placed at the bottom tip of the wick drain was used to hold the wick drain in place when the mandrel was being withdrawn. At locations where anchoring was not occurring, a water pump was connected to the mandrel and water pressure was used to hold the anchor in place while the mandrel was being retracted.

7.2 Wick Drains and Anchors

The installed wick drains were manufactured by Enka Solutions and provided by Menard Canada. They were made from polymeric materials, with semirigid cores that were 100 mm wide and 2 mm thick. The filter jacket geotextile was a heat-bonded nonwoven with a thickness of 0.5 mm.

The anchors used to hold the wick drains in place were provided by Menard Canada. The steel anchors were 1 mm thick, 85 mm wide, and 180 mm long each. Once pushed into the ground, the edges of the anchor bend, which will decrease the resulting smear zone area and provide better anchorage for the installed wick drains.

7.3 Wick Drain Installation

A uniform 2 m spacing (square pattern) laid out by RLO was followed by Menard Canada. Evolution placed 0.5 to 1 m thick waste rock over the entire wick drain area prior to start of installation, to provide a suitable base for construction equipment to traffic on. Since the wick drain equipment cannot push through waste rock, RLO excavated trenches along each planned wick drain line and backfilled the trenches with sand.

The depths of the wick drains varied from 6 m to 23 m across the work area. At each location, Menard attempted to push the mandrel until the wick drain machine refused in dense soil. Refusal was generally achieved during the installation, except for 250 installed wick drains where resistances observed during the installation as well as borehole data of the surrounding area indicated that the mandrel had moved beyond the glaciolacustrine clay layer and had been terminated in underlying silt or sand layers.

8 INSTRUMENTATION AND MONITORING

8.1 Instrumentation Overview

There are a total of 10 vibrating wire piezometers installed in the normally consolidated clay layer in the SD1 crest and downstream area, as shown in Figure 5.

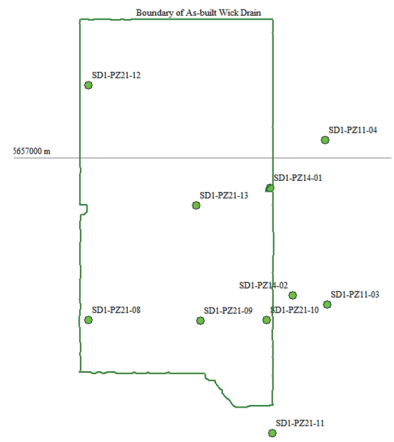


Figure 5. Location plan of piezometers installed in SD1 downstream and crest area

SD1-PZ11-03 and SD1-PZ11-04 were installed through the SD1 crest in July 2011. SD1-PZ14-01A and SD1-PZ14-02A were installed in the downstream area in June 2014. The remaining VWPs were installed in the downstream area in October 2021 (after the wick drain installation in July 2021). Waste rock fill was placed in lifts (1 m or less each lift) over the SD1 downstream and crest area from the period of July to November 2021, after the wick drain installation.

8.2 Measured Piezometric Elevations

Figure 6 presents the measured piezometric elevations with time at the piezometers installed in SD1 downstream and crest area.

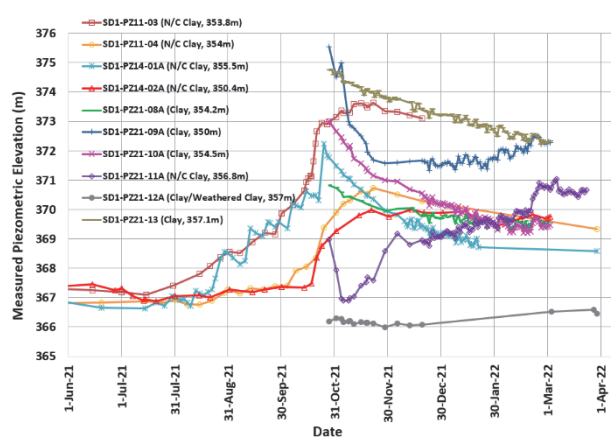


Figure 6. Measured piezometric elevations with time at piezometers installed in SD1 downstream and crest area

The following observations can be made from the measured piezometric data in Figure 6:

- The four piezometers installed in the area outside of the wick drain area showed slower pore water pressure dissipation rates than those installed within the wick drain area after the measured piezometric elevations reached their peaks due to waste rock placement. This suggests that the wick drains did increase the pore water pressure dissipation rates in the clay layer, as expected.
- The pore water pressure dissipation rate for each piezometer is different due to differences in placed waste rock fill thickness, distance to nearby rock drains, and distance to vertical drainage boundary.
- The measured piezometric elevation at SD1-PZ21-09A decreased sharply in late October to mid-November but suddenly stopped decreasing in late November, and even slightly increased with time after the end of January of 2022. The exact reason for this trend is not clear and is still under investigation.
- It appears that the excess pore water pressure at SD1-PZ21-12A was fully dissipated before this piezometer was installed. The tip for this piezometer was only 0.71 m from the bottom drainage layer (sand till) and a thinner rock fill (1.57 m) was placed after the wick drain installation. The tip is located at the boundary between the weathered clay and the NC varved clay layer. The total thickness of the weathered clay and the NC clay is only 2.44 m at this location. All these factors promote faster/earlier dissipation of the excess pore water pressure.

9 BACK-ANALYSES WITH MEASURED DATA

9.1 Comparison with Designed Cases

SD1-PZ14-01A was installed in 2014 (well before the wick drain installation in 2021) and on the edge of the wick drain zone (see Figure 5). This piezometer captured the initial pore water pressure increase due to the waste rock placement loading and later then the pressure dissipation with time. It provides a good set of data to compare the actual measured data with that from numerical consolidation analyses using the parameters assumed for the design of the wick drains.

Two-dimensional numerical consolidation analyses using SIGMA/W were conducted for four cases (T1 to T4). Case T1 simulates the case without wick drains or the case when wick drains are assumed to be completely malfunctional. The analysis for Case T1 modelled a clay layer of 7.62 m thick with both top and bottom vertical drainage boundaries. The analysis results at the depth of 3.68 m from the top drainage boundary (i.e., the tip depth of SD1-PZ14-01A) for this case is shown in Figure 7. The results suggests that the vertical direction drainage plays a minimal role at SD1-PZ14-01A even though a reasonably upper value (1.1E-3 cm^2/s) of C_v was used.

The plan layout of SD1-PZ14-01A relative to the nearby as-built wick drains indicates that the drainage conditions around SD1-PZ14-01A are three-dimensional, including both the horizontal drainage towards the nearby wick drains and the vertical drainage towards the top and bottom of the vertical drainage boundaries. Nevertheless, the results for Case T1 suggest that the vertical direction drainage plays a minimal role at SD1-PZ14-01A. Therefore, we can simplify the three-dimensional configuration by ignoring the vertical drainage effects and simulating the horizontal (or lateral) drainage conditions at SD1-PZ14-01A as a two-dimensional planar (or horizontal) slice.

Cases T2 to T4 simulate a planar slice through the tip location of SD1-PZ14-01A. The smear zone equivalent diameter of 0.42 m was calculated assuming three times of the equivalent diameter of the anchors used for the wick drain installation for this project.

The results in Figure 7 suggest that the pore water pressures at SD1-PZ14-01A dissipated much faster than those predicted from the analyses using the parameters assumed for the design of the wick drains (Cases T2 and T3). Even using C_v of 1.1E-01 cm^2/s, C_h/C_v of 10 (this is a typical value for varved clay in literature), and k_h/k_s of 8 for Case T4, the actual pore water pressure dissipation was still faster than the predicted. This suggests that the actual C_v of the clay could be higher than 1.1E-3 cm^2/s, especially during the early stage of consolidation.

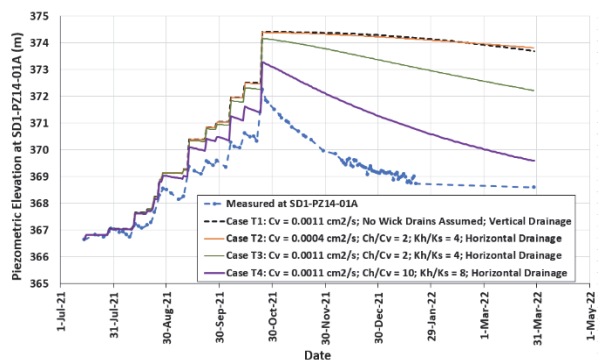


Figure 7. Comparison of measured piezometric elevations at SD1-PZ14-01A with modelled results for Cases T1 to T4.

9.2 Consolidation Parameters from Back-Analysis

Additional two-dimensional numerical consolidation analyses were conducted to estimate the clay consolidation parameters by matching the measured data at SD1-PZ14-01A. Table 4 lists the parameters that result in a good match with the measured data, as shown in Figure 8.

Table 4. Consolidation parameters from back-analyses to match measured piezometric data at SD1-PZ14-01A

Days after July 15, 2021	C_v (cm^2/s)	C_h/C_v	k_h/k_s
0 to 40	2.0E-03	10	1
41 to 160	1.5E-03	10	4
161 to 258	1.1E-03	10	8

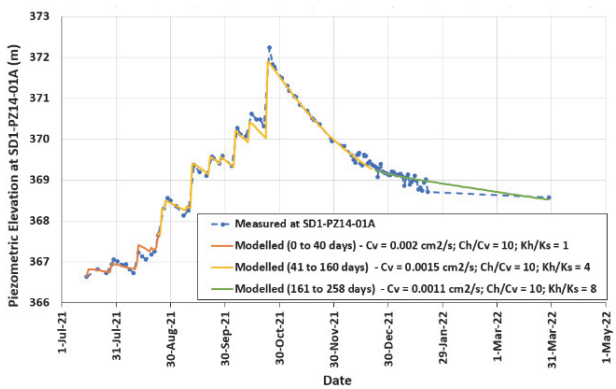


Figure 8. Comparison of measured and matched analysis results at SD1-PZ14-01A

The back-analysis results suggest that the C_v values could decrease with clay consolidation, as indicated in Table 4. The smear zone consolidation parameters may also change with progress of consolidation – the ratio of k_h/k_s increasing with consolidation time. In another word, the hydraulic conductivity (k_s) or coefficient of consolidation of the smear zone may decrease with consolidation time, approaching to the vertical hydraulic conductivity or coefficient of vertical consolidation for the NC clay during the later stage of consolidation. It appears that a C_h/C_v ratio of 10 for the varved clay is reasonable. The C_v values from the back-analyses are consistent with the upper range of the C_v values from the laboratory tests and calibrated analyses, as shown in Figure 3.

It is interesting to note that Dittrich et al. (2010) also indicated that the ratio of k_h/k_s appeared to increase with consolidation time based on the back-analyses of the measured piezometric data from several embankment construction sites in Northern Ontario, where wick drains were installed in a clay layer. They found that the mean value of k_h/k_s from the four sites was 6 for the early stage of consolidation ("early time") and 8.5 for the late stage of consolidation ("end-time"), which is comparable with k_h/k_s of 1 to 4 during the early stage of consolidation and 8 during the later stage of consolidation from this study. Dittrich et al. (2010) noted that the theoretical decrease in the permeability of soil during consolidation is the most likely explanation of why the value of k_h/k_s increases (or k_s decreases with time) from the "early-time" data to the "end-time" data.

10 SUMMARY AND DISCUSSIONS

Wick drains were designed and successfully installed in a normally consolidated glaciolacustrine clay layer in the downstream foundation of an existing tailings dam (SD1). Numerical consolidation analyses were conducted to assist in the assessment and design of the wick drains.

Ten vibrating wire piezometers were installed in the normally consolidated clay layer in the SD1 crest and downstream area. The four piezometers installed in the area outside of the wick drain area showed noticeably slower pore water pressure dissipation rates than those installed within the wick drain area after the measured piezometric elevations reached their peaks due to waste rock placement. This suggests that the installed wick drains did increase the pore water pressure dissipation rates in the clay layer, as expected.

Numerical consolidation analyses were conducted to compare the measured piezometric data at one piezometer (SD1-PZ14-01A) with those predicted from the consolidation analyses using the parameters assumed for the wick drain design. The results suggest that the pore water pressures at SD1-PZ14-01A dissipated much faster than those predicted from the analyses, indicating that the parameters adopted for the wick drain design were on the conservative side.

Additional numerical consolidation analyses were conducted to estimate the clay consolidation parameters by matching the measured data at SD1-PZ14-01A. The back-analyses suggest that the Cv values could decrease with clay consolidation. The hydraulic conductivity (or coefficient of consolidation) of the smear zone may also decrease with consolidation time. The C_v values from the back-analyses are consistent with the upper range of the C_v values from the laboratory tests and calibrated analyses. It appears that a C_h/C_v ratio of 10 for the varved normally consolidated clay is reasonable.

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