

Observational Approach to Construction over Soft Tailings

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ABSTRACT: Operation and closure of tailings storage facilities frequently requires construction over soft tailings, such as fill placement associated with dam construction during operation or cover placed for closure and reclamation. Challenges faced during construction over soft tailings are primarily related to the low strength and high compressibility of the material, which can lead to difficult construction conditions and increased costs. It is often thought that ground improvement is required to provide a stable foundation. However, proper application of soil mechanics principles and engineering judgment based on field observations can eliminate the need for costly ground improvement techniques. The case history presented in this paper describes an alternative approach consisting of staged construction over soft tailings through the use of in-situ and laboratory testing, as well as review of field instrumentation data in accordance with the Observational Approach. This method has facilitated successful ongoing construction over soft tailings without costly ground improvement techniques.

1 INTRODUCTION

At many tailings storage facilities, construction of dams during operation or placement of cover during closure and reclamation requires construction over soft tailings. The low strength and high compressibility of this material presents challenges, often leading to the use of costly ground improvement methods such as wick drains or foundation reinforcement.

In the case history presented in this paper, the authors describe successful implementation of the offset upstream construction method at a low-seismicity, cold-climate tailings storage facility without use of costly ground improvement techniques. As described herein, instrumentation monitoring and field performance data were used in accordance with the Observational Approach to successfully complete construction without ground improvement.

2 BACKGROUND

The authors were hired to evaluate initial offset upstream construction completed using ground improvement techniques that included wick drains and geotextile reinforcement. Instrumentation monitoring data obtained during construction was evaluated and a geotechnical investigation was completed to gain a better understanding of the engineering properties of the underlying fine tailings/slimes deposit. This allowed subsequent construction to be completed without ground improvement.

3 USE OF THE OBSERVATIONAL APPROACH

Design based on the most unfavorable assumptions is inevitably uneconomical; however, it provides some degree of assurance that a soil-supported structure will not develop unanticipated defects. Nonetheless, when design permits, making construction modifications that consider the most probable rather than the most unfavorable conditions can result in large savings. Using the Observational Approach introduced by Peck (1969), information and data gaps are filled by monitoring during construction and the design is modified, as needed.

As demonstrated by this case study, the Observational Approach can be used to improve designs and reduce construction costs, particularly in the case of tailings impoundment dams.

4 OFFSET UPSTREAM CONSTRUCTION METHOD

The offset upstream construction method allows tailings dams to be raised without increasing the overall footprint of the tailings storage facility. This technique, introduced in the early 1990s at the tailings storage facility, uses a staged construction approach. Initial dam construction materials (coarse tailings in this case) are placed during the winter over frozen fine tailings/slimes using lightweight earthwork equipment. After the surface of the fine tailings/slimes thaws the following summer, additional dam construction material is placed above the winter fill to complete the dam raise.

A section of the offset upstream construction at the tailings storage facility is illustrated in Figure 1. Figure 1 also shows the perimeter dam, which was constructed above competent native soils using a combination of downstream, centerline, and upstream construction methods. The perimeter dam retains fine tailings/slimes which were deposited prior to offset upstream construction and are used as the foundation for the offset upstream dam.

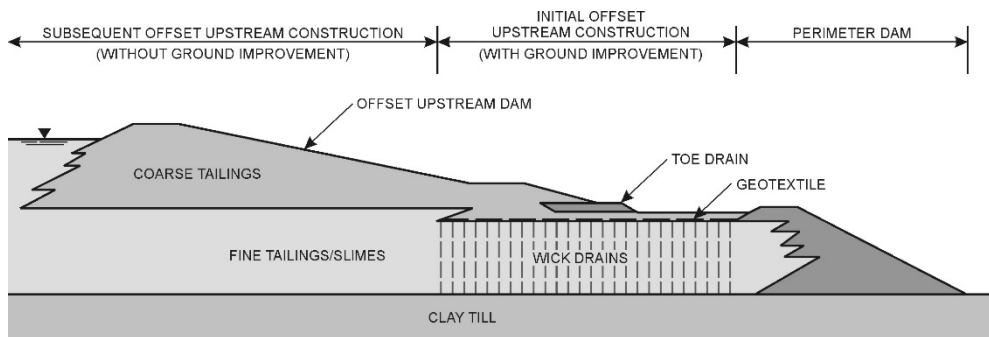


Figure 1. Offset Upstream Construction

The offset upstream construction method was used for several reasons. First, continuation of the perimeter dam construction method would result in high uplift pressures immediately upstream of the perimeter dam. The offset upstream construction method pushes the pond further upstream, which helps minimize pore-water pressures at the perimeter dam. Second, downstream and centerline construction methods are considered more expensive and less flexible. Third, the use of coarse tailings as a construction material allows a waste product of the mining process to be used beneficially. In addition, select clay borrow was becoming less available. Though construction over fine tailings/slimes presents challenges due to the low strength and compressibility of the material, these challenges can be overcome through use of appropriate construction staging and the Observational Approach.

5 INITIAL OFFSET UPSTREAM DAM CONSTRUCTION

Initial offset upstream dam construction at the tailings storage facility incorporated ground improvement techniques. These included installation of wick drains and use of geotextile for

foundation reinforcement, as shown in Figure 1. According to the previous designers, the wick drains were installed to expedite primary consolidation, improve the overall seepage regime, and mitigate liquefaction potential. The geotextile was used to reinforce the coarse tailings foundation and provide a stable working platform during construction. Initial offset upstream dam construction phase included two stages, as described below.

5.1 Stage 1

The offset upstream dam foundation consisted of 1.2 m of coarse tailings placed during the winter over previously deposited fine tailings/slimes which were allowed to sufficiently freeze prior to construction. A geotextile was placed within the coarse tailings, approximately 0.6 m above the surface of the fine tailings/slimes.

Prior to placement of the first layer of coarse tailings, pneumatic piezometers were installed to monitor pore-water pressures within the fine tailings/slimes deposit. Settlement plates were also installed to monitor displacement at the interface of the coarse tailings and the frozen fine tailings/slimes.

5.2 Stage 2

After the fine tailings/slimes underlying the offset upstream dam foundation had thawed the following summer, wick drains were installed in a square pattern, spaced 3 m apart. These penetrated the fine tailings/slimes deposit (approximately 18 m thick) and toed into the top of the underlying native glacial till.

Following wick drain installation, additional coarse tailings fill was placed in lifts. The thickness of the additional coarse tailings was approximately 2.4 m, giving a total fill thickness (winter foundation plus summer construction) of approximately 3.6 m.

This two-stage construction method allowed for comparison of the fine tailings/slimes response to fill placement and dam performance under two conditions: (1) initial winter foundation without wick drains and (2) summer construction with wick drains.

6 INSTRUMENTATION MONITORING

As previously indicated, prior to Stage 1, pneumatic piezometers and settlement plates were installed at the site. This instrumentation provided valuable data to help assess consolidation characteristics of the fine tailings/slimes under load, with and without wick drains. Observations made from instrumentation monitoring data are included below.

6.1 Pore-Water Pressure Distribution

Figure 2 shows the typical pore-water pressure distribution within the fine tailings/slimes deposit and underlying native soils in an area without wick drains. The hydrostatic pore-water pressure line is included in Figure 2 for reference. The pore-water pressure distribution indicates that there are downward flow conditions within the fine tailings/slimes at the site. The downward flow conditions differed from models prepared by the previous designers, which assumed the bottom glacial till to be impervious, resulting in hydrostatic pore-water pressure distribution within the fine tailings/slimes deposit.

The native foundation soils typically observed across the tailings storage facility include glacial till above fractured bedrock. At some locations, a sand layer is present between the glacial till and the bedrock. Although the glacial till consists of a relatively impermeable clay material, it is believed to be discontinuous and contain preferential flow paths to the fractured bedrock. This creates the downward flow condition, resulting in an increased effective stress (compared to hydrostatic conditions) that is favorable for overall stability (Davies et al., 2002). Additionally, the discontinuity within the glacial till allows the fine tailings/slimes deposit to be doubly drained (both upward and downward), increasing the rate of consolidation.

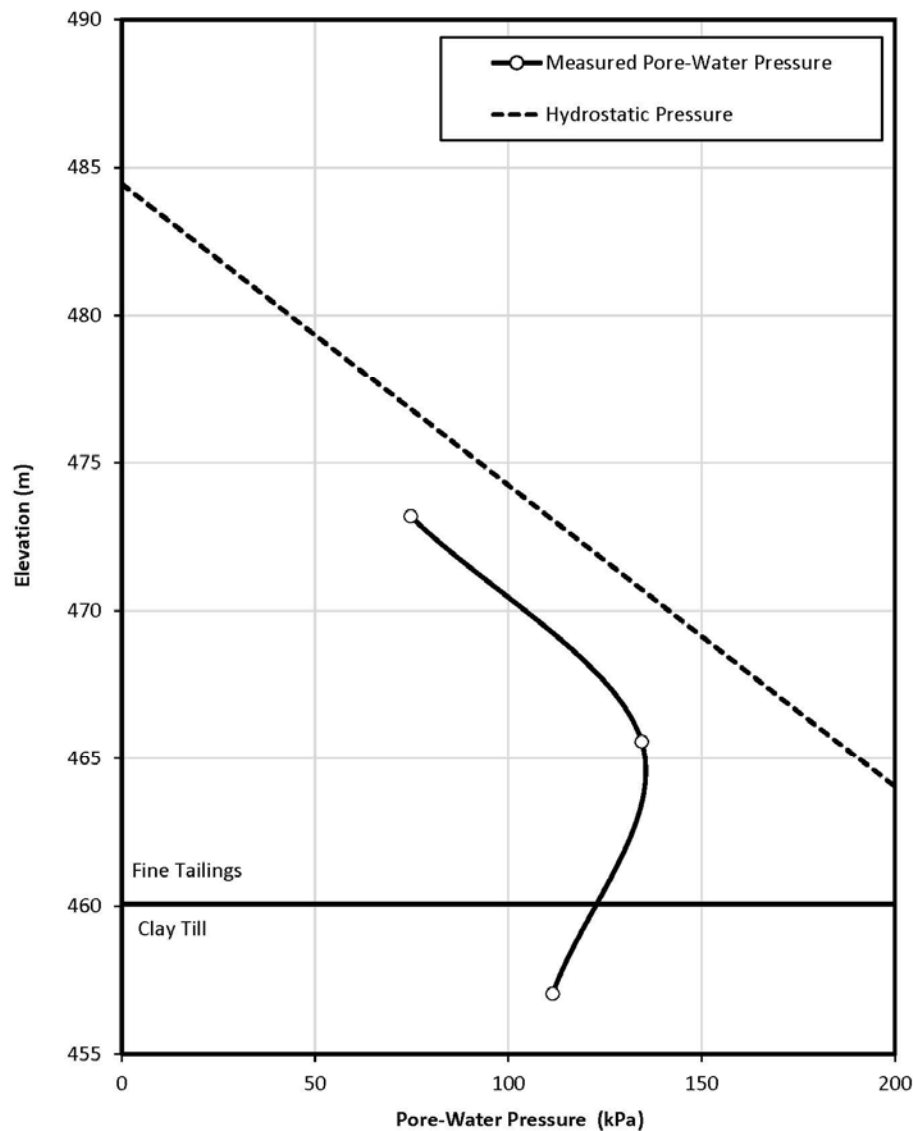


Figure 2. Typical Pore-Water Pressure Distribution in Area without Wick Drains

6.2 Excess Pore-Water Pressure

Figure 3 shows a comparison of excess pore-water pressure versus time at three locations along the dam alignment, before and after wick drain installation. The measurements were obtained using pneumatic piezometers installed approximately 4.6 m below the surface of the fine tailings/slimes. The open symbols in Figure 3 correspond to measurements taken prior to wick drain installation (Stage 1). The closed symbols correspond to measurements taken after wick drain installation (Stage 2). As shown in Figure 3, maximum excess pore-water pressures prior to wick drain installation ranged from approximately 24 to 28 kPa and dissipated in approximately 130 to 170 days (by extrapolation due to piezometer damage during construction). After wick drain installation, the maximum excess pore-water pressures ranged from approximately 36 to 43 kPa and dissipated in approximately 60 to 200 days. Note that the piezometer at location C was damaged before an accurate assessment of dissipation time could be made. This indicates that the wick drains expedited excess pore-water pressure dissipation at only some locations. It should also be noted that the difference in thickness of fill placed during Stages 1 and 2 (approximately 1.2 m vs. 2.4 m) caused the difference in peak excess pore-water pressures between the two stages.

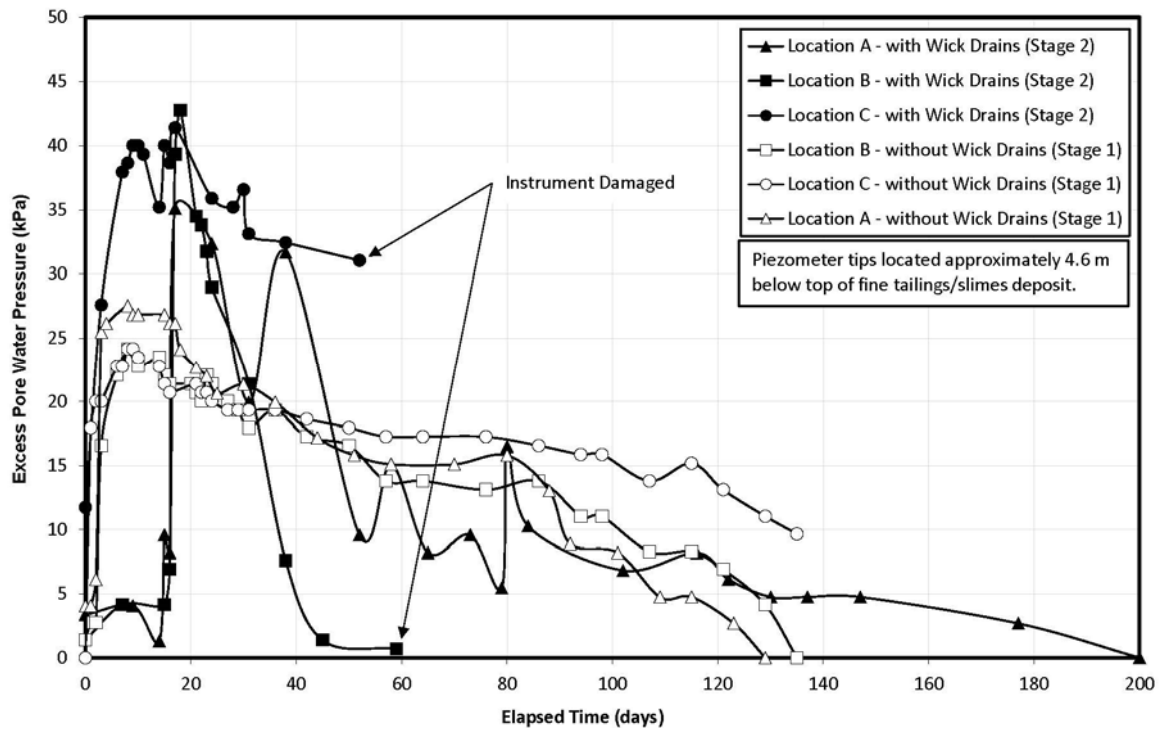


Figure 3. Comparison of Excess Pore-Water Pressure vs. Time in Fine Tailings/Slimes Deposit at 4.6 m with and without Wick Drains

Figure 4 shows a comparison of the measured excess pore-water pressure versus time at two locations along the dam alignment before and after wick drain installation. Excess pore-water pressures at these locations were measured using pneumatic piezometers installed approximately 20 m below the surface of the fine tailings/slimes deposit. The open symbols in Figure 4 correspond to measurements taken prior to wick drain installation (Stage 1). The closed symbols correspond to measurements taken after wick drain installation (Stage 2). As shown in Figure 4, the maximum excess pore-water pressures prior to wick drain installation ranged from approximately 12 to 15 kPa and dissipated in approximately 130 to 160 days. The maximum excess pore-water pressures after wick drain installation ranged from approximately 13 to 20 kPa and dissipated in approximately 130 to 180 days (by extrapolation due to piezometer damage during construction). Figure 4 shows that excess pore-water pressure was generally the same with and without wick drains. This indicates little-to-no improvement in dissipation rate through the use of wick drains.

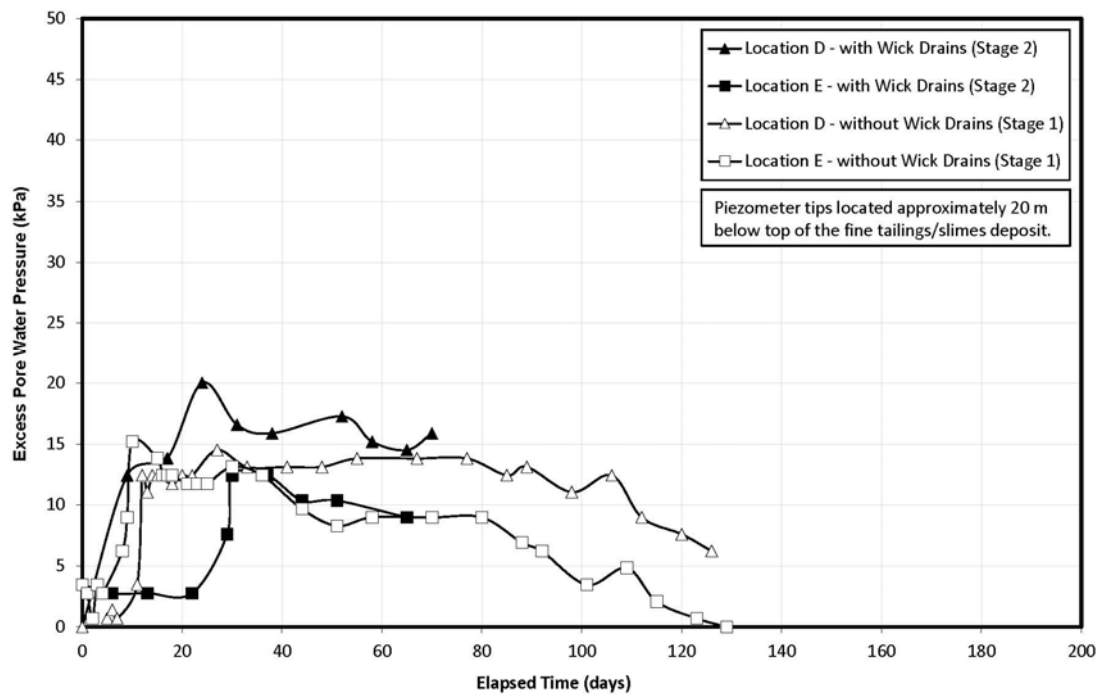


Figure 4. Comparison of Excess Pore-Water Pressure vs. Time in Fine Tailings/Slimes Deposit at 20 m with and without Wick Drains

6.3 Settlement

Figure 5 shows settlement due to offset upstream construction, as measured by 18 settlement plates along the dam alignment. The settlement resulting from the initial placement of the coarse tailings during Stage 1 (approximately 1.2 m thick) ranged from 0.4 m to 0.75 m, with an average of 0.5 m before installation of the wick drains. After installation of the wick drains and placement of the second layer of coarse tailings during Stage 2 (approximately 2.4 m thick), the total settlement ranged from 0.7 m to 1.4 m, with an average of approximately 0.8 m after an elapsed time of 420 days.

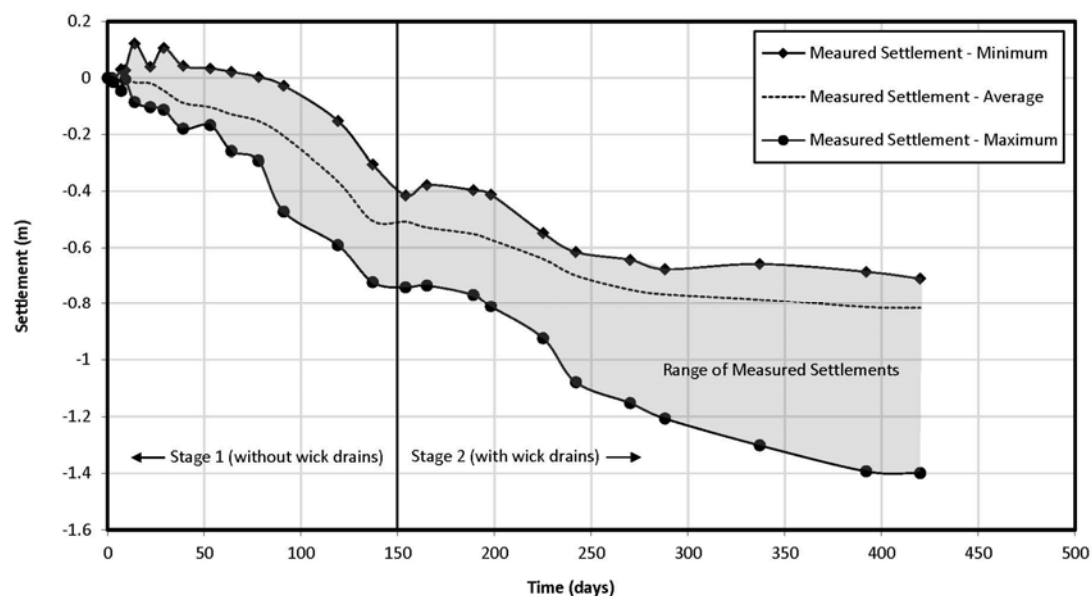


Figure 5. Measured Settlement during Stage 1 (without Wick Drains) and Stage 2 (with Wick Drains)

6.4 Observations

Instrumentation monitoring data illustrated in Figures 3 through 5 shows:

1. At shallow depths (i.e. less than 4.5 m), wick drains may provide slightly faster dissipation of excess pore-water pressures at some locations (see Figure 3).
2. At greater depths (i.e. 20 m), excess pore-water pressures are not affected by the presence of wick drains (i.e. wick drains did not significantly improve drainage).
3. Excess pore-water pressures generated during offset upstream construction without the use of wick drains dissipated in approximately 130 to 170 days. As such, if staged construction is properly implemented and excess pore-water pressures are allowed to dissipate prior to placement of additional fill, use of wick drains is not required. However, if the construction sequence changes or is accelerated, wick drains may be needed.
4. The measured settlement illustrated in Figure 5 shows that the settlement during Stage 1 (i.e. without wick drains) was, on average, 0.5 m after 150 days, roughly corresponding to the dissipation of the excess pore-water pressure. Similarly, after application of the second layer in Stage 2 (i.e. with wick drains) the total settlement averaged approximately 0.8 m after 420 days.

Upon review of the construction records and instrumentation monitoring data, it became apparent that additional analysis, including in-situ and laboratory testing, could be performed to establish whether wick drains and geotextile were required in future offset upstream construction, provided staged construction was completed with sufficient time for consolidation to occur between stages. As a result, a geotechnical investigation was performed and is described below.

7 GEOTECHNICAL INVESTIGATION AND FIELD PERFORMANCE

The primary objective of the geotechnical investigation was to obtain additional fine tailings/slimes compressibility and strength data through field and laboratory testing. The laboratory testing included consolidation testing using oedometer and triaxial devices. The field testing included cone penetration test (CPT) soundings with pore-water pressure dissipation testing.

The discussion below will focus on the fine tailings/slimes compressibility. This is the primary factor influencing the generation and dissipation of pore-water pressure and, subsequently, determining whether wick drains are required. Of particular interest is the coefficient of consolidation (c_v), related to the time rate of settlement (similarly, excess pore-water pressure dissipation during consolidation). The coefficient of consolidation was determined from CPT dissipation tests, laboratory testing, and field performance during offset upstream construction.

7.1 c_v from CPT Dissipation Tests

Dissipation tests were performed by stopping the advancement of CPT soundings and measuring the decrease in excess pore-water pressure with time. The rate of excess pore-water pressure dissipation depends on the coefficient of consolidation. The coefficient of consolidation from the dissipation test is generally determined using the time at which 50% of excess pore-water pressures generated during sounding advancement have dissipated (t_{50}). The procedures developed by Robertson et al. (1992) and Burns and Mayne (1998) were used to estimate the coefficient of consolidation in this assessment.

7.2 c_v from Laboratory Oedometer and Triaxial Tests

The coefficient of consolidation was measured in the laboratory using oedometer and triaxial tests performed on samples collected during the geotechnical investigation. The oedometer tests include consolidation of slimes placed by slurry in the testing apparatus. In the triaxial test, deformation of a triaxial specimen upon load application was measured until the end of primary consolidation was reached. In both tests, the coefficient of consolidation was estimated using Terzaghi's theory of consolidation for each load increment (Equation (1) below).

7.3 c_v Back-Calculated from Field Performance

The coefficient of consolidation was also back-calculated using field performance data and the equations shown below.

$$c_v = \frac{TH^2}{t} \quad (1)$$

$$c_v = \left(\frac{1}{\gamma_w}\right) \left(\frac{k}{m_v}\right) \quad (2)$$

Equation (1) is derived from Terzaghi's theory of consolidation and uses the time factor (T), the time for excess pore-water pressure dissipation (t), and drainage path length (H). Equation (2) uses the permeability (k), the coefficient of volume compressibility (m_v), and the unit weight of water (γ_w). The time factor (at 95% of consolidation) and unit weight of water are constants. The time for excess pore-water pressure dissipation was determined based on piezometer data, as described above. The drainage path length was determined based on knowledge of the fine tailings/slimes deposit and the underlying native soils. The coefficient of volume compressibility was calculated based on settlement, loading, and effective stress data, and the permeability was determined using CPT dissipation testing. Permeability values based on CPT dissipation testing were viewed as more representative of field conditions than laboratory testing because of variability within the fine tailings/slimes deposit.

Figure 6 shows the coefficient of consolidation versus effective stress using CPT dissipation tests, oedometer tests, triaxial tests, and back-calculations from field performance. The range of coefficient consolidation values is between approximately 0.1 m²/yr and 850 m²/yr over an effective stress range of approximately 1 to 10,000 kPa. Typical values range from approximately 10 to 200 m²/yr.

The coefficient of consolidation from laboratory testing was generally found to be lower than the value obtained from CPT dissipation tests. The geometric mean coefficients of consolidation from laboratory testing and CPT dissipation testing were 23 m²/yr and 58 m²/yr, respectively. This difference suggests that layering within the fine tailings/slimes deposit enhances drainage and produces a higher coefficient of consolidation than laboratory testing. The difference is also attributed to the use of mostly slimes for laboratory testing, which have a higher fines content and thus lower coefficient of consolidation than fine tailings.

Based on field performance, the geometric mean coefficient of consolidation was found to be 76 m²/yr. This value is similar to the value obtained based on CPT dissipation test and is judged reasonable due to the layering effects described above. The geometric mean value of all data is 40 m²/yr.

Based on these results, analyses were performed to predict the excess pore-water pressure dissipation and evaluate the stability of the offset upstream dam. The evaluation of the proposed design modifications and construction of the offset upstream dams without the use of wick drains is discussed below.

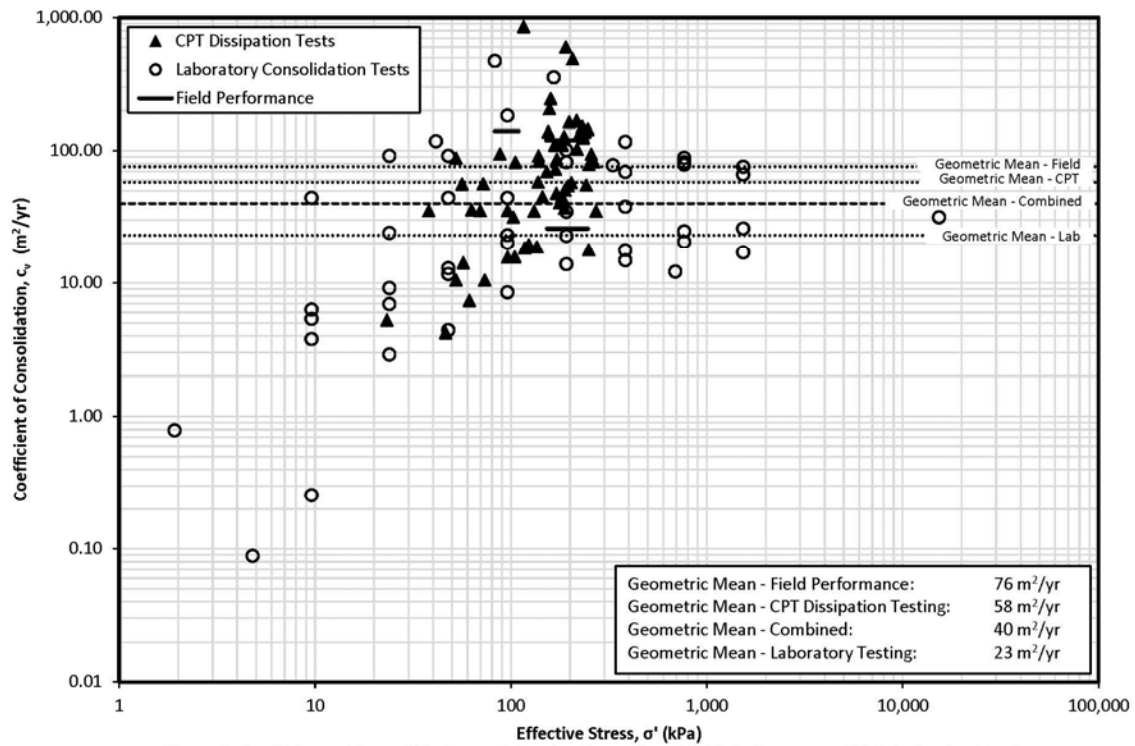


Figure 6. Coefficient of Consolidation vs. Effective Stress from Field Performance, CPT Dissipation Testing, and Laboratory Testing

8 MODIFIED APPROACH TO OFFSET UPSTREAM CONSTRUCTION

Due to continuous tailings storage facility operation, design and construction of additional impoundment dam raises were required. This provided the opportunity to use offset upstream construction without foundation improvement (i.e. wick drains and geotextile). The modified approach to offset upstream construction consisted of two stages, as explained below.

8.1 Stage 1

The offset upstream dam foundation consisted of coarse tailings placed during the winter over previously deposited fine tailings/slimes that were allowed to freeze prior to construction. A thicker 3.0-m layer of coarse tailings was used (compared to 1.2 m in the original method). This allowed for a more stable foundation that did not require geotextile or other reinforcement. Based on field observations, it was determined that the thicker foundation would still allow the underlying frozen fine tailings/slimes to thaw prior to Stage 2 construction.

Prior to placing the foundation layer, settlement plates were installed. Nested vibrating wire (VW) piezometers were also installed within the fine tailings/slimes deposit and underlying native soils using the fully grouted method (Contreras et al., 2007).

8.2 Stage 2

Following Stage 1 of offset upstream construction, a waiting period of approximately 4 to 6 months was required to allow excess pore-water pressures to dissipate prior to additional fill placement and for the underlying fine tailings/slimes to thaw. During this time, excess pore-water pressure dissipation was monitored using the VW piezometers located beneath the dam fill and settlement plates at the surface of the fine tailings/slimes were used to measure consolidation. Test pits were used to confirm that the fine tailings/slimes had sufficiently thawed prior to placement of additional fill.

After the fine tailings/slimes thawed and excess pore-water pressures had been substantially dissipated, additional coarse tailings fill was placed in layers approximately 30 cm thick until the dam raise was completed.

The geotextile was eliminated from the design because (1) stability modeling indicated it was not required for short- or long-term stability of the offset upstream dam and (2) predicted offset upstream dam deformation was judged acceptable without it. Similarly, seepage analyses showed that the wick drains did not significantly improve the overall seepage and pore-water pressure distribution under the offset upstream dam. Wick drains also do not allow rapid pore-water pressure dissipation during fast loading, which is required to mitigate liquefaction. The discharged capacity of the wick drains used was not high enough to provide the required drainage; thus, they were eliminated from the design.

9 PREDICTION AND PERFORMANCE OF MODIFIED OFFSET UPSTREAM CONSTRUCTION METHOD

Prior to implementation in the field, the modified offset upstream construction approach was simulated through computer modeling. The modeling was completed using the GeoStudio software suite, as well as information collected from the geotechnical investigation and field performance assessment. The following discussion compares predicted and actual performance of the offset upstream construction in terms of settlement and excess pore-water pressure.

Figure 7 shows coarse tailings fill thickness, measured settlement, and measured excess pore-water pressure with respect to time during offset upstream dam construction. As shown, settlement due to placement of the initial foundation layer (Stage 1) was between approximately 0.5 and 2.0 m at approximately 150 days after initial fill placement and prior to subsequent construction lifts (Stage 2). The predicted settlement after 550 days is approximately 2.1 m, which is within the range of the measured settlement. After placement of the second coarse tailings layer, the measured settlement increased to between 1.4 and 3.1 m after an elapsed time of approximately 550 days.

Figure 7 also includes the predicted and measured excess pore-water pressures during offset upstream construction. As previously described, piezometers were installed after the Stage 1 fill was placed, which allowed drill rig access over the fine tailings/slimes. The measured excess pore-water pressure at the time of piezometer installation ranged from approximately 1.7 to 3.0 m of pressure head due to Stage 1 construction. Excess pore-water pressures decreased to less than approximately 2.0 m of head before Stage 2 construction began at approximately 150 days. The predicted excess pore-water pressure during this time period is somewhat higher than the measured values.

Following placement of Stage 2 coarse tailings fill, excess pore-water pressures increased to between approximately 5.0 and 7.5 m of pressure head. The excess pore-water pressure and fill height plots in Figure 7 show that construction of Stage 2 was completed in approximately 75 days. Based on the measured excess pore-water pressure, the end of primary consolidation (as indicated by zero excess pore-water pressure) occurred at approximately 450 days or 300 days after the start of Stage 2 construction. This is somewhat longer than the dissipation time at Locations A through E (see Figures 3 and 4), because the fine tailings/slimes deposit is thicker at Locations F and G. The predicted maximum excess pore-water pressure shown in Figure 7 is between the measured values at Locations A and B, and the computed time to the end of primary consolidation is somewhat longer than measured in the field.

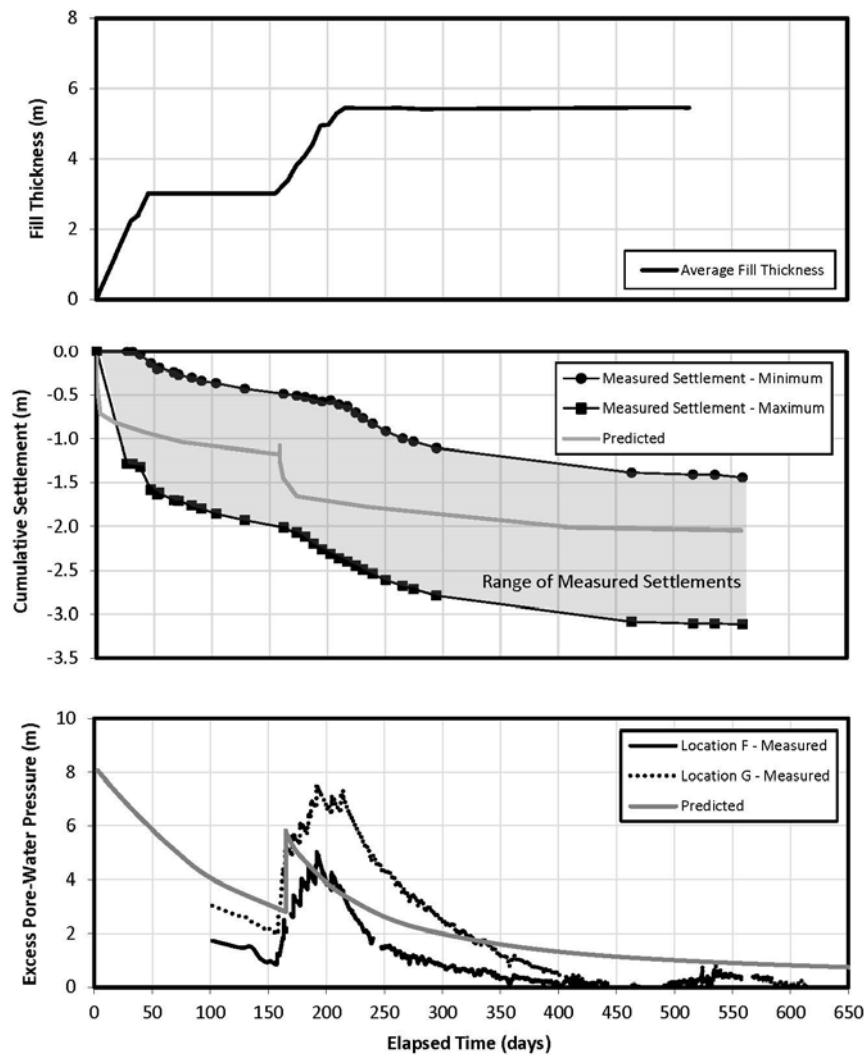


Figure 7. Fill Height, Settlement, and Excess Pore-Water Pressure vs. Time during Offset Upstream Construction without Wick Drains

10 SUMMARY AND CONCLUSIONS

The offset upstream construction method uses staged construction and placement of coarse tailings fill over previously deposited fine tailings/slimes. The initial fill placement is performed in the winter while the fine tailings/slimes delta is frozen, which provides a stable working platform. After the fine tailings/slimes material has thawed and excess pore-water pressures have substantially dissipated, additional fill material is placed to complete the dam raise.

The low strength and compressibility of the fine tailings/slimes can lead to stability, deformation, and constructability concerns. This has traditionally been resolved by relying on costly ground improvement techniques such as wick drains and geotextile foundation reinforcement.

Using the Observational Approach, however, the offset upstream construction method has been successfully completed without relying on ground improvement methods. The modified approach was the result of:

- An assessment of field performance and instrumentation monitoring data that suggested wick drains were not required if the construction schedule allowed enough time for excess pore-water pressures to dissipate.
- A geotechnical investigation to obtain additional field information and samples for laboratory testing and subsequent data for computer modeling.

- Computer modeling to assess the feasibility of a modified construction approach prior to implementation in the field.

Used for numerous dam raises, this modified approach has resulted in significant cost savings.

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