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Two case studies: efficient design of mine structures using the observational approach at Kearl

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ABSTRACT

A geotechnical design for mine structures should address two basic requirements: safety and economics. Most conventional geotechnical designs focus on deterministic approaches with economics being evaluated afterwards despite the fact that the observational approach has been well established by geotechnical practitioners for decades, which allows for non-deterministic outcomes. This paper presents two case studies, in which the observational approach was successfully applied to the design and construction of mine structures at Imperial's Kearl oil sands mine. The first case study demonstrated efficiencies by embracing a 3D limit equilibrium method for the mine pit walls where the 2D analysis results did not meet the target Factor of Safety. The second case study relied on the observational approach in mitigating potential inflow from the Basal or Devonian aquifers under an in-pit tailings dyke. Both cases demonstrated significant economic efficiencies being achieved for oil sands mine operations while maintaining appropriate safety standards for the structures.

RÉSUMÉ

Un modèle géotechnique de structures minières devrait répondre à deux exigences fondamentales: la sécurité et le coût. La plupart des modèles conventionnelles géotechniques se concentrent sur des approches déterministes, le coût étant ensuite évaluée malgré le fait que l'approche observationnelle est bien comprise et appliquée par les ingénieures en géotechnique depuis des décennies. Ce document présente deux études dans lesquelles l'approche observationnelle a été appliquée avec succès à la conception et à la construction des structures minières de la mine de sables bitumineux de l'Impériale Kearl. La première étude a démontré des gains d'efficacité en adoptant une méthode d'équilibre en 3D pour les parois de la mine où l'analyse en 2D ne pus atteindre le facteur de sécurité ciblé. La deuxième étude se focalise sur l'approche observationnelle pour faire face aux afflux potentiels des aquifères basaux ou dévoniens sous une digue de résidus miner dans la mine. Les deux cas ont démontré des gains économiques importants pour les opérations de la mine de sables bitumineux. Les deux cas ont démontré des gains économiques importants pour l'exploitation de la mine de sables bitumineux tout en maintenant des normes de sécurité appropriées pour les structures.

1 INTRODUCTION

The Alberta oil sands contains approximately 27 billion m^3 of bitumen at depths sufficiently shallow to be commercially surface-mined. These operations encompass the removal of mine waste and ore, which in turn forms pit walls, and utilizes earth dams to store process water for bitumen extraction and impound tailings after the oil is removed. These large earth structures are typically designed using general geologic information, discrete subsurface boreholes, piezometric data and laboratory testing on selected samples to characterize foundation conditions and material properties.

Generally, initial geotechnical designs focus on deterministic approaches using the aforementioned information with economics being evaluated afterwards. A geotechnical design for mine structures, however, should address two basic requirements: safety and economics. Geotechnical engineers are often faced with the difficult task of finding the balance between the economics and the safety related likelihood of large slope failures, which in some cases can translate into designs that are either too conservative or overly aggressive. The observational approach developed by Peck (Peck, 1969) allows for assurance of safety as well as economic considerations, provided the design can be modified in a timely manner as construction progresses.

This paper presents two case studies, in which the observational approach was successfully applied to the mine structures at Imperial's Kearl oil sands mine (Kearl). The first case study demonstrated efficiencies by embracing a three dimensional (3D) limit equilibrium method for the mine pit wall where 2D analysis did not meet the target Factor of Safety (FoS). The second case study involved addressing the risk of potential inflow from Basal or Devonian aquifers under an in-pit tailings dyke, in which shutdown recovery tests were conducted to confirm whether or not potential conduits or cracks exist in the Devonian aquitard or in the Lower McMurray muds. The designs in both case studies ensured that the risk of slope failure or inflow was appropriately managed while concurrently optimizing economic gains.

2 PROJECT OVERVIEW

2.1 Site Geology

Imperial Oil Resources Limited (IORL) has developed an oil sands mine at its Kearl lease, located approximately 70 km north of Fort McMurray, Alberta (Figure 1), the mine requires large earth structures for safe operation, such as pit walls and ex-pit and in-pit tailings dams.

Geomorphology of the Kearl lease is a result of a complex glacial history consisting of multiple glacial ice advances and retreats, glacial thrusting and the associated sedimentation, melt-water processes, and remobilization of sediments. Glacially deposited Quaternary soils, generally consisting of tills and outwash sands and silts, unconformably overlie fluvially deposited Cretaceous deposits of Upper (UKm), Middle (MKm) and Lower (LKm) Members of the McMurray Formation. The Lower McMurray generally comprises an upper unit of flood plain silts, muds and coals, which typically govern the slope stability of pit walls and in-pit mine structures, and a lower unit of fluvial sand, in which the Basal aquifer exists. The Devonian succession underlies the Cretaceous deposits and consists of several units, an upper aquitard unit with relatively low conductivity and a lower higher permeability reef unit, in which one of the Devonian aquifers exists.

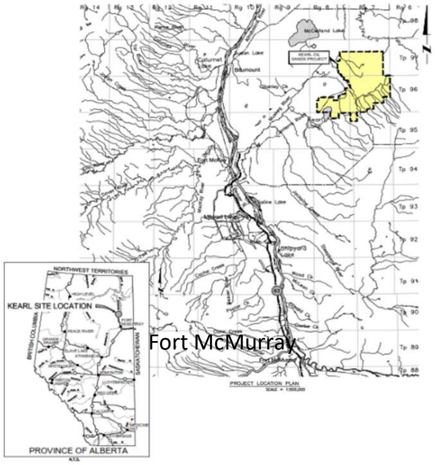

Figure 1. Kearl site location plan

2.2 Objectives of Efficient Designs

Mine structures have to be designed in a safe manner, which usually requires the factors of safety of the mine structures to meet the design criteria. However, mining operations need to deal with a highly variable environment and materials, which result in a degree of uncertainty related to geotechnical slope design. Mining structures cannot be too conservatively designed as this will negatively impact the mine's profitability, hence design approaches to reduce risk and ensure safe and effective operation are critical. The scale of the structures and the potential for more efficient designs (i.e.; realization of most likely conditions at that scale) makes application of an observational method worthwhile.

2.3 Observational Approach

The Observational Approach developed by Peck has been successfully applied to Geotechnical designs and construction over many decades since its inception. It should not be used, however, unless the designer has developed mitigations for every unfavourable situation that might be disclosed by the observations. In addition, the observations must be reliable (Peck, 1969).

3 CASE STUDY 1: 3D SLOPE STABILITY ANALYSIS OF PIT WALLS

3.1 Background

In the framework of slope stability analysis, the vast majority of analyses are performed in 2D under the assumption of plane strain conditions. The plain strain assumption is valid if one dimension is very large. However, the majority of slopes, both natural and constructed, exhibit complex 3D configuration due to irregular mine pit crest alignment, resulting from discontinuous geologic formations. Analyses of ideal slopes indicated that the 3D FoS can be 10% to 80% (Chugh 2014) or in some cases, 100% (Quinn 2014) higher than the resulting 2D FoS. The 3D analysis, in this case, represents most likely conditions where the 2D analysis represents a "simplified" more conservative (or worse case) condition. As a result, 3D analysis can provide potential opportunities to ensure slope stability while saving operational costs or maximizing profits by optimizing the slopes of the pit walls, and recovering more of the resource.

3.2 2D Limit Equilibrium Analysis (LEA) of pit walls

The pit wall slopes for the 2016-2017 pit advance at Kearl had initially been designed based on 2D LEA, in which seven cross sections were analyzed. 2D analysis of three sections, Sections A, B and H (Figure 2), resulted in a FoS (e.g., Figure 3) that necessitated mitigations in the event these conditions existed in the slopes. Buttresses were designed in order to meet the FoS criteria for these three sections. While advancing to final pit slopes, movement within the controlling foundation unit (i.e. LKm muds) accelerated to 4 mm/day, exceeding previous observations, which forced mining within the area to be redirected away from ultimate limits. A 2D LEA was performed utilizing the as-built geometry and measured pore pressure conditions from the instrumentation network. The results indicated that an offset of approximately 50 m should be maintained from the final pit wall on the bottom bench to maintain the FoS criteria (Figure 4). As a result, 750 m^3 of ore per meter was left along the pit wall to meet FoS criteria. Based on observations, a construction trigger rate of 4 mm/day for three consecutive readings was adopted. This allowed mining to continue and provided more time to complete further 3D LEA.

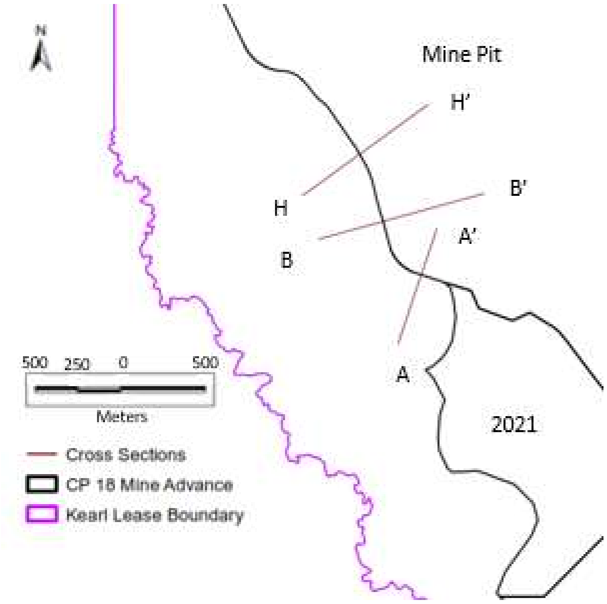

Figure 2. Pit advance (2016-2017) and section plan view

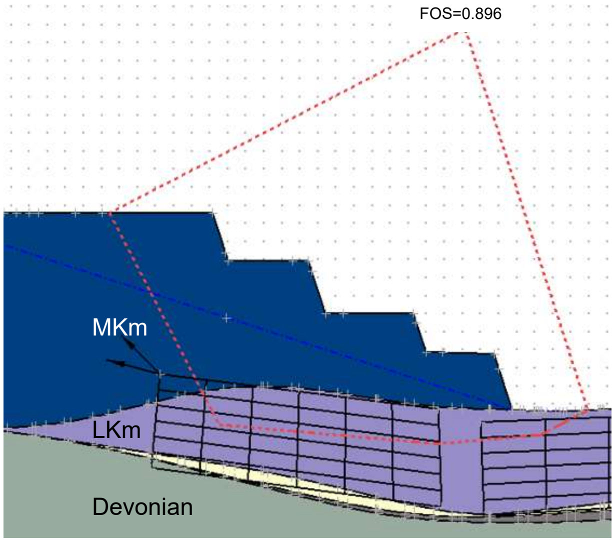

Figure 3. The 2D FoS of Section A

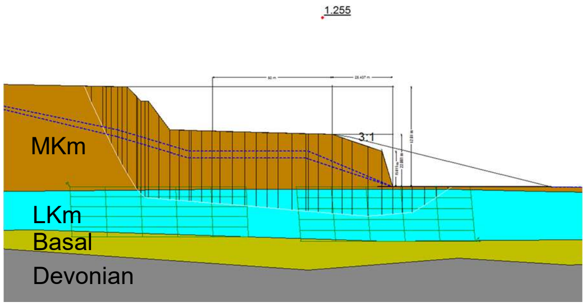

Figure 4. The 2D FoS of Section A with As-built Geometry

3.3 3D LEA

As it can be seen in the 2D analysis (e.g. Figure 3), the slip surface passes through complex geometries with the stronger MKm formation overlying the weaker LKm formation. In order to analyze the effects of complex geometries, 3D LEA (SVSlope3D v5.4.08) was employed.

The 3D FoS and slip surfaces at Section A are shown in Figure 5 (2D view) and Figure 6 (3D view). The relative shape of the 2D and 3D slip surfaces are similar when compared in 2D. The shape of the 3D slip surface provided valuable information to be utilized when creating an execution plan. With the increase in FoS in 3D, an ore buttress was deemed unnecessary, allowing for the excavation of ore to the original limits of the bottom bench.

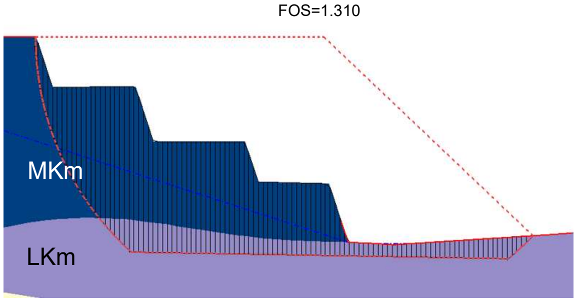

Figure 5. 2D view of 3D slip surface in sliding direction (Section A)

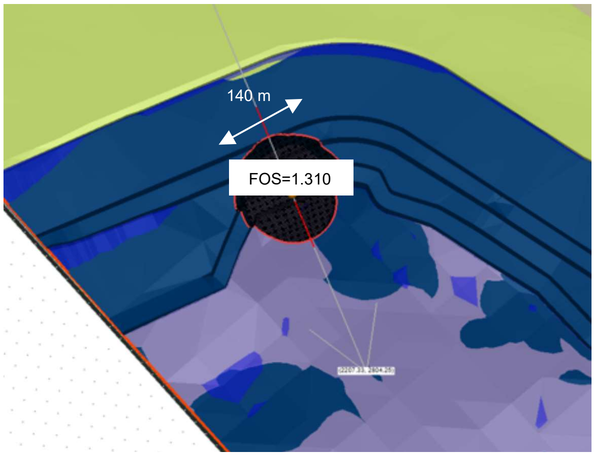

Figure 6. Isometric view of 3D slip surface (Section A)

3.4 Comparison of FoS between 2D and 3D LEA

Table 1 summarizes the 2D and 3D FoS comparison for the three sections. The 3D LEA resulted in an increase in FoS ranging between 21% and 46%, relative to the FoS determined through 2D LEA. This increase in FoS corresponds to the findings in the reviewed literature. The difference in percent increase from Section A compared to the others is likely due to the concave shape of the pit in the Section A area. This shape increases the resisting forces along the sides of the slip surface, therefore increasing the FoS.

Table 1. Comparison of FoS between 2D and 3D LEA

Section	2D	3D	Increase (%)
A	0.896	1.310	46
B	0.873	1.053	21
H	0.929	1.164	25

3.5 Execution

The 3D FoS presented in Table 1 are above unity but in some cases remain below the design criteria of 1.2. Experience at Kearl indicated that the strength of the LKm unit is usually higher than the conservative assumed design strength. Therefore, an alternative method was proposed that would maintain slope stability while increasing ore capture: excavate the remaining ore and replace with a waste buttress a maximum of 100m behind the excavation, a long known method of mining, sometimes referred to as bonus ore. The waste buttress geometry was designed using 2D LEA (10 m V x 50 m H).

A comprehensive execution plan was developed utilizing the 3D LEA results. The following sections provide methods used to appropriately manage potential risks. These methods include geotechnical surveillance, staged excavation and contingency plans.

3.5.1 Geotechnical Surveillance

Geotechnical instrumentation was installed on the El. 310 m (crest) and El. 280 m (mid slope) benches along the ultimate limits. The instrumentation included vibrating wire piezometers (VWPs), which measured pore water pressure in key geologic units (e.g., LKm muds) and slope inclinometers (SIs) that measured subsurface movement. Typical geotechnical instrumentation arrangement along the final limits is shown on Figure 7 in which the green lines represent the final bench crest and toe limits. Visual observations and instrumentation was collected and analyzed daily during mining. It should be noted that remote monitoring was utilized as access to these instrumentation locations was limited.

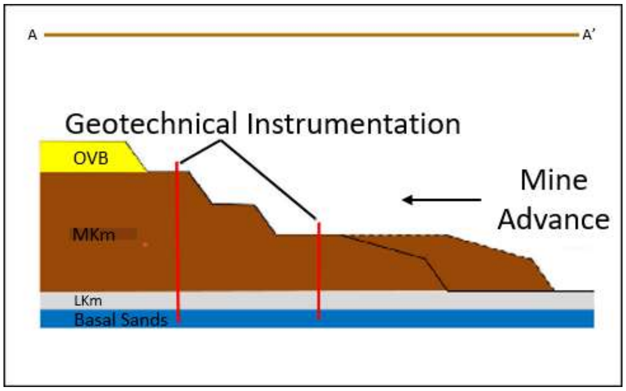

Figure 7. Typical geotechnical instrumentation arrangement along the final limits.

3.5.2 Stages of Excavation

Excavation was restarted adjacent to instrumentation to provide slope performance monitoring coverage. The excavation configuration consisted of a 3H:1V push down slope followed by the advancing shovel face (two benches of ore formed the 50 m wide interim buttress). First, the pushdown slope was re-established and then the shovel face was advanced towards final limits. It was expected that the majority of the movement would be observed as the shovel face advanced towards final limits. A visual representation of the mining configuration in relation to instrumentation is provided in section AA' on Figure 7.

The mine and replace strategy for excavating to final limits is described as follows:

- Excavate the final benches,
- Replace with buttress fill material concurrently once space is available.
- The maximum unsupported strike of wall between mining and buttress construction was 100 m as informed by the 3D analysis. A visual representation of the mine and replace strategy is provided in Figure 8, where the dark blue solid represents the remaining ore and the light blue solid represents the waste buttress fill following the excavation.
- Additionally, as a precaution in the event of poor slope performance, a safe area to relocate equipment was identified daily and communicated to mine operations.
- Lastly, daily instrumentation data collection and visual inspections along the crest and toe was performed during execution to assess slope performance.

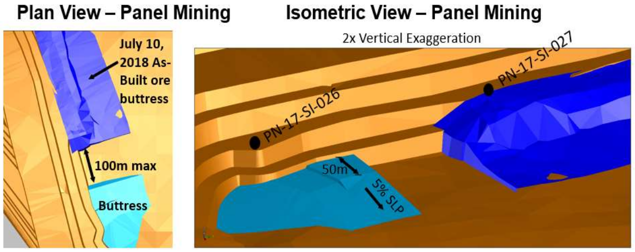

Figure 8. Visual representation of the mine and replace strategy.

3.5.3 Contingency Mine Plan

The final criteria for the advancement to final limits was the preparation of a contingency plan to address the possibility of slope movement exceeding maximum thresholds, resulting in the slope being no longer safe to mine as originally planned. If these levels of movement were observed, the contingency plan required excavation activities to halt, followed immediately by buttressing the slope until slope movement rates were observed to be tolerable. Should an increase of buttressing have been deemed necessary, it was required that the buttress construction start against the ore toe of the pit slope and continue away from the face towards the middle of the pit.

3.5.4 Results

Excavation of the opening strike began October 6, 2018 adjacent to instruments PN-18-SI-028 and PN-17-SI-25 and progressed to the south from the north. At these locations minimal deflection was recorded. A photo of mine and replacement strategy is provided in Figure 9, which was taken from the ore crest showing the opening strike and buttress construction. The double bench configuration was split once the buttress was built to the crest elevation of the bottom design bench to maximize ore capture. As the excavation approached within 50 m of PN-18-SI-27, deflection within the LKm shear zone accelerated to 2.8 mm/day. As the excavation passed, movement slowed down to 0.3 mm/day. Cumulative deflection plots for instrument PN-18-SI-027 are provided in Figure 10 in which 11 mm cumulative deflection in the LKm shear zone, in response to mine and replace strategy was observed at ≈El. 246 m or ≈10m below the pit floor. These observations were within safe operating thresholds. The displacement vs time relation for instrument PN-18-SI-027 is plotted in Figure 11, in which shear zone deflection measured in response to initial excavation and mine and replace strategy showed stable trends.

Figure 9. Photo taken from ore crest showing the open cut and buttress construction.

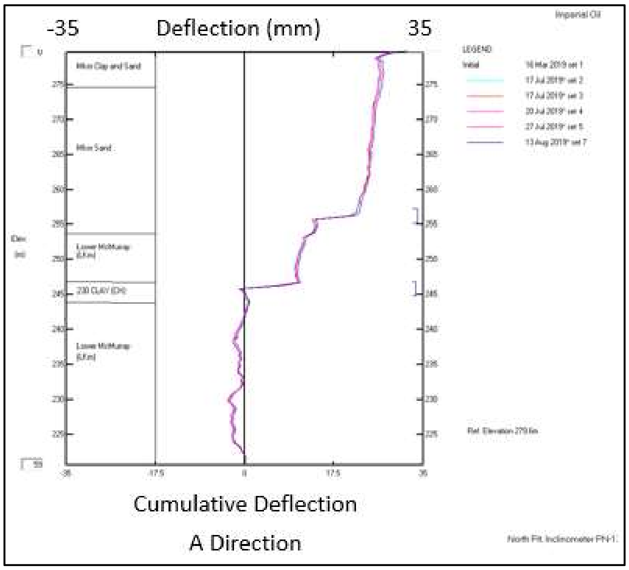

Figure 10: Cumulative deflection plots (PN-18-SI-027)

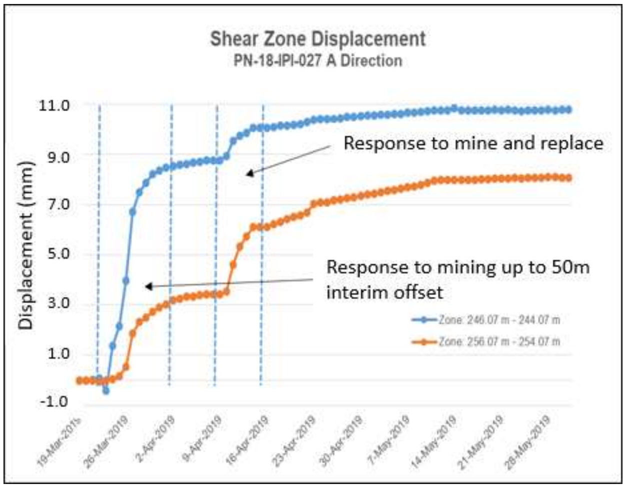

Figure 11. The displacement vs time relation (PN-18-SI-027)

Generally, slope movement was detected as the excavation approached within about 650 m of the final pit wall instrumentation and slowed as the excavation passed. From these observations the strike of the active slip surface was estimated to be approximately 130 m, which is consistent with the 3D LEA prediction. Removal of the temporary ore buttress was successful and the observations gathered supported the 3D analysis results.

4 CASE STUDY 2: SHUT-DOWN RECOVERY TEST FOR THE FOUNDATION CHARICTERIZATION OF AN IN-PIT DAM

4.1 Background

The first in-pit tailings dyke at Kearl was built on a foundation of the Lower McMurray and in some areas directly on Devonian aged units, where the Lower McMurray was not present. The limestone is usually a competent foundation for the in-pit dyke structure provided the limestone is intact without cracks or conduits. Following a saline inflow originating from a deep Devonian aquifer that occurred in 2010 in another oil sands mine (Mahood, 2012), the oil sands industry, including IORL made the effort to understand the root cause of the inflow and to help mitigate future Devonian-related incidents. At Kearl, a series of Devonian groundwater depressurization wells have been installed and operated to mitigate the potential risk of a similar inflow event.

4.2 Geological uncertainty at Kearl

The core and seismic data from Kearl demonstrated the dissolution of at least 200 meters of soluble material from the Prairie Evaporite Formation (Walker et al., 2015). Removal of this material resulted in the collapse of the overlying Waterways Formation and resulted in the creation of undifferentiated breccia. This dissolution event may have created potential conduits from Devonian aquifer to shallower elevations (Figure 12). There are, however, some uncertainties regarding the conduits and one of the key uncertainties is the location of the potential conduits. How to deal with this uncertainty in the design becomes critical for both safety and economics. If there is potential for inflow from a foundation aquifer during the service life of a dam, it is common practice to install a foundation drain system to manage expected inflow into the dyke from potential conduits within the foundation. Construction of a foundation drainage system between the foundation and the starter dyke can cost tens of millions of dollars for a large-scale earth structure. Therefore, it is worthwhile to verify whether any conduits exist within the foundation of the dyke footprint or not. If a lack of conduits can be confirmed in the dyke footprint within the underlying foundation, then a foundation drainage system would not be required.

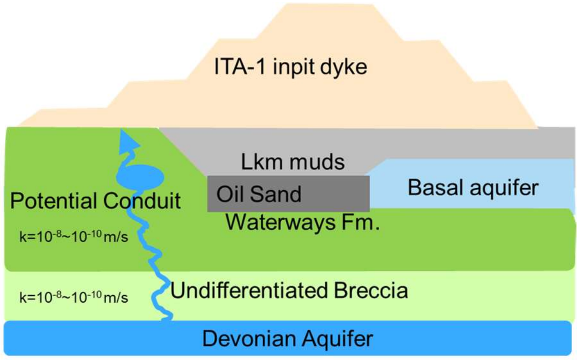

Figure 12. Schematic geological profile of the dyke and the foundation

4.3 Shutdown recovery test

In order to confirm the uncertainty of the location of the conduits in the foundational Devonian units, a shutdown recovery test in the Devonian pumping wells was proposed and conducted. The testing program procedure is described as follows:

- Prepare the foundation by removing excess material or debris within the area of interest;
- Turn off the Devonian depressurization wells or reduce the pumping rates for a period (e.g., weeks to months) until the hydraulic head in the Devonian aquifer recovers to a steady state, approximately 20-30 m above the base of feed (BOF) (i.e., top of the dyke foundation);
- Observe response at the BOF by recording semi-quantitative data;
- Review response of the VWPs in different units especially in Devonian aquitard (Waterways Formation and undifferentiated breccia);
- Collect water samples from select seeps and test for water chemistry; and
- Analyze the collected data.

The Devonian depressurization wells were turned off on February 7, 2018 and resumed pumping on April 4, 2018.

4.4 Test results

4.4.1 Visual Observations

Over the period during which the Devonian shutdown recovery test was conducted, 11 localized seeps (Figure 13) were observed in the exposed BOF area. Of these 11 seeps, four were located within the dyke footprint. All 11 seeps stopped flowing between two and five months after they were first observed, all within the testing period.

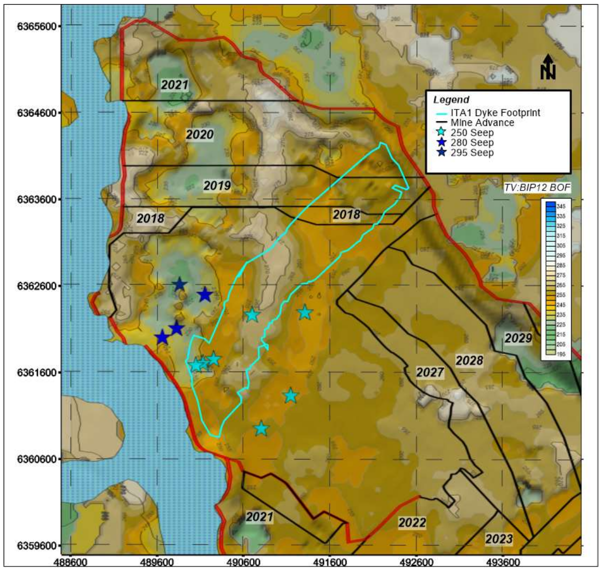

Figure 13. Locations of the observed seeps

4.4.2 Piezometric response

Records from 12 VWPs installed in the Devonian aquitard (Waterways) were available from this test period. Of the 12 VWPs, only one showed an increasing trend, four tips showed a decreasing trend, which was determined to be a result of stress relief from mine excavation. The remaining seven tips had negligible to no response to the hydraulic head increase in the Devonian aquifer (Figure 14).

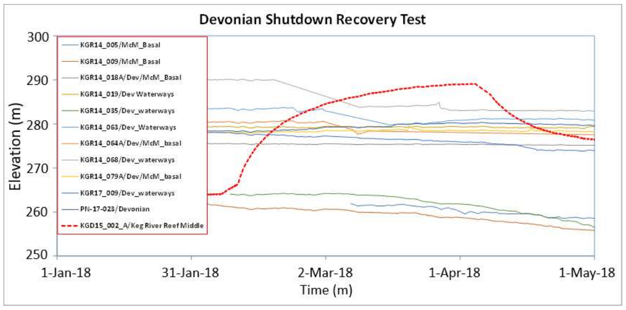

Figure 14. Piezometric data collected during the test period

4.4.3 Water Chemistry Analysis

The groundwater types commonly encountered at Kearl are illustrated on Figure 15. The Devonian aquifer is a Ca + SO_4 type water and is generally non-saline in the north pit; total dissolved solids (TDS) <4,000 mg/L. Basal water is generally HCO_3 with no dominant cations. Locally, the Basal aquifer has elevated SO_4, Cl and TDS, which is interpreted as mixing with the Devonian aquifer. The Quaternary aquifer is predominantly of Ca + Mg - HCO_3 + CO_3 type with TDS concentrations generally less than 500 mg/L.

Four samples were collected from seeps during the shutdown-recovery test and sent to the lab for analysis. The results were plotted on the Figure 15 to compare with the common groundwater types at Kearl. Two of the samples resembled typical Quaternary type water. The other two samples had elevated Na, Cl, HCO_3 and TDS concentrations, which is closer to Basal type water chemistry.

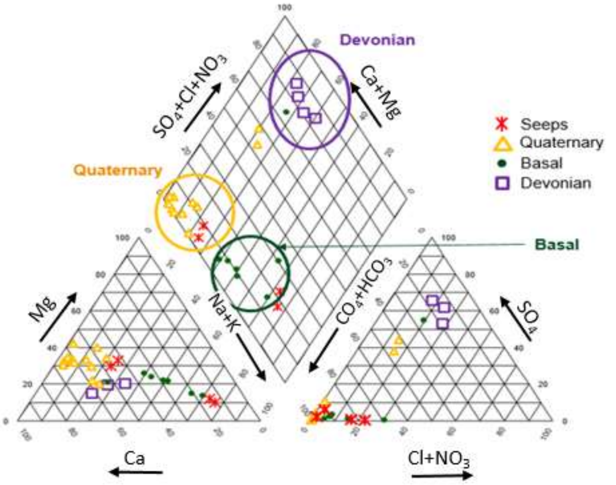

Figure 15. Piper graphs for the water chemistry

4.5 Summaries of the test results

Based on visual observations, piezometric response data and water chemistry, the seeps that were observed during the shutdown recovery test period were not considered to originate from the Devonian aquifer. Although two of the four samples had Basal signatures, the 11 seeps observed stopped flowing during test period; therefore, the seeps were not considered to be directly from the basal aquifer either.

After the shutdown recovery test data was evaluated, it was determined that a full sand blanket on the starter dyke foundation was not required as specific seep locations had been identified and thus could be individually mitigated. This resulted in a reduction of hauling and placement of approximately 1.5M m^3 of clean sand.

5 CONCLUSIONS

Both of the examined cases demonstrated significant economic efficiencies being achieved for oil sands mine operations while maintaining appropriate safety standards for the structures.

Acknowledgements

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