Quality Control Considerations for Overburden Earth-fill Tailings Dam Construction in the Oil Sands

by

Christopher Davies

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Department of Civil and Environmental Engineering
University of Alberta

ABSTRACT

Quality control and construction methods for an oil sands overburden tailings dam in the Albertan Oil Sands can differ from these conventional construction methods due to two governing factors: A high overburden to ore ratio with a complex geology requiring significant waste management effort and a year-round aggressive construction schedule in a northern climate.

Dyke 10 is a large earth-fill tailings dam, located at Canadian Natural Resources Limited (CNRL)'s Horizon Oil Sands mine, approximately 80 km north of Fort McMurray, Alberta. This thesis synthesizes the experiences gained during the construction of Dyke 10 project to illustrate how construction and quality control methods used at an oil sands overburden tailings dam differ from conventional practice. A review of published literature was used to summarize the state of practice in the industry. A site visit, accompanied by interviews with CNRL construction personnel, compaction data, and limited associated reporting made available by CNRL was used to develop the findings of this thesis.

The management of overburden waste requires a comprehensive understanding of the geological block model combined with collaborative mine planning and an effective dispatch system is necessary to manage the mobilization of up to 350,000 m^3 of fill per day. Dyke 10 has been designed in a robust manner to accommodate a broad range of fill types comprised of overburden waste from the mine, thereby reducing the need for storage of overburden elsewhere.

A combination of method and performance based specifications are used at Dyke 10. The method based controls and their management are built upon industry experience, then expanded upon with modern technology and equipment resulting greater rates of production. Empirical

trials such as test fills are used to establish construction methodology and expected fill performance for year round construction.

CNRL's quality control and quality assurance methods have had to adapt to the rapid rate of construction, by establishing a controlled system that is consistent and repeatable. The predominant quality control approach used at Dyke 10 is the reliance on detailed and well documented observations by qualified personnel corroborated by periodic compaction density and index testing in manner that is representative of placed material.

Quality control measures must adapt to the construction methods to satisfy that the evaluating criteria are representative and fit for function. While the quality control system applied at Dyke 10 has proven effective, a similar approach may not be applicable for dam construction on a smaller scale, or where design necessitates a narrow range of material controls.

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To Roya, I'm forever grateful for the years of love, laughter, and patience you've given. I look forward to our many adventures and memories to come.

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1.0 Introduction

Quality control measures for conventional earth fill dam construction are well documented in published literature such as U.S Department of the Interior Bureau of Reclamation., (1998), Fell et al (2005) and many others. In general terms, construction of such a structure entails the selection and specific placement of appropriate materials that satisfy a narrow range of engineering characteristics. Standardized testing protocols are applied to control the construction methods and ensure that the desired engineering characteristics of the placed materials are achieved.

Typical testing protocol may include the performance of in-situ density testing in conjunction with Standard Proctor values. Earth fills are placed in lifts often between 0.15 m to 0.3 m thick and compacted with conventional rollers and compacters within the tolerances established by standard proctor results. Quality assurance and quality control personnel monitor and test the works to satisfy that the specifications have been met. Construction is limited by weather and climate, as fill placement is typically not undertaken during rainfall or frozen conditions due to the difficulties in achieving specified density criteria under such conditions.

Quality control and construction methods for an oil sands overburden tailings dam in the Albertan Oil Sands can differ from these conventional construction methods due to two governing factors:

- A high overburden to ore ratio with a complex geology requiring significant waste management effort
- Year-round aggressive construction schedule in a northern climate

Modern mining methods in the Albertan Oil Sands can mobilize materials on a scale of 25 Mm^3 per year (Cameron, 2013), requiring unique waste management strategies. The incorporation of waste materials into dam construction can be an effective method to optimize finite storage space on site. However, complex geology in the region results in a broad range of material types that limit the effectiveness of conventional quality control efforts.

Based in a northern Canadian climate, winter conditions are present for several months of the year. Despite this climate, operational and business needs of oil sands mine operators necessitate tailings dam construction to continue year-round on a 24/7 basis.

The unique conditions encountered in the oil sands has promoted innovation to develop construction methods that satisfy the production targets. Utilizing large volumes of a broad range of waste materials is a driving component of dam design. Lifts of materials are commonly placed with thicknesses on the scale of 1 m. Large haul trucks function as not only a method of transporting materials but serve as compaction equipment to densify the thickly placed lifts. These significant deviations from standard practice require the development of quality control techniques that satisfy that the placed materials are fit for function.

Dyke 10 is a large earth-fill tailings dam, located at Canadian Natural Resources Limited (CNRL)'s Horizon Oil Sands mine, approximately 80 km north of Fort McMurray, Alberta. This thesis synthesizes the experiences gained during the construction of Dyke 10 project to illustrate how construction and quality control methods used at an oil sands overburden tailings dam differ from conventional practice.

1.1. Documentation and Literature

A literature review was conducted, focusing on construction methodology and technology as it pertains to oil sands tailings dams constructed out of overburden materials. Conventional construction and quality control measures were summarized, along with notable papers on implications of large scale earth dam construction.

Documentation was provided by CNRL. These included:

- A general design cross section of Dyke 10 and fill specifications (CNRL, 2011),
- Compaction data with an example monthly data summary, from 2006 to 2015 (CNRL, 2015),
- A test pit field study memorandum (Thurber, 2005),
- Quality Assurance and Quality Control Procedures (CNRL, 2006),
- Dyke 10 construction monthly QA/QC presentation (CNRL, 2015),
- A semi-annual Mine Geotechnical Review Board presentation (CNRL, 2012),
- CNRL Dyke 10 Interburden Compaction Trial for Zone 1 Fill letter report (AMEC, 2009).

- Select Dyke 10 Construction photos (CNRL, 2018)

1.2. Interviews

A site visit to CNRL's Horizon Oil Sands site was conducted on September 30th, 2015 to interview site personnel and observe construction of Dyke 10. CNRL staff personnel Mr. Walday Abeda, Mr. Jeff Obrigewitsch, and Mr. Toks Adebayo were interviewed as part of the visit. The site visit focused on understanding the sourcing of materials, construction sequence, and quality controls.

Off-site interviews were conducted with Mr. Jeff Obrigewitsch, as well as available industry experts who volunteered their time. These included Mr. Bill Chin of Klohn Crippen Berger and Mr. Gerry Ferris of BGC Engineering Inc.

1.3. Organization of Thesis

This thesis has been organized into 4 chapters including this introductory chapter (**Chapter 1**):

Chapter 2 Provides an overview of construction methodology for oil sands tailings dams comprised of overburden materials, with consideration to relevant conventional dam construction. The geological setting, oil sands mining process and an overview of tailings is included.

Chapter 3 Provides a project description of Dyke 10. The mine planning and material utilization techniques employed are explored along with their influence on the geotechnical design of the structure. Construction methodology and quality control measures for the structure are presented.

Chapter 4 provides the thesis conclusions and recommendations for future considerations.

2.0 Oil Sands Mining Process

A compilation of literature is provided below. The review is focused on the geotechnical considerations for large scale dam construction as it relates to the oil sands industry.

2.1. Geological Setting

Alberta's oil sands contain approximately 270 billion m^3 of bitumen, with about 60% of it estimated to be recoverable by surface mining practices (Morgenstern & Scott, 1997). The Athabasca deposit near Fort McMurray (Figure 1) has undergone the bulk of development for commercial mining.

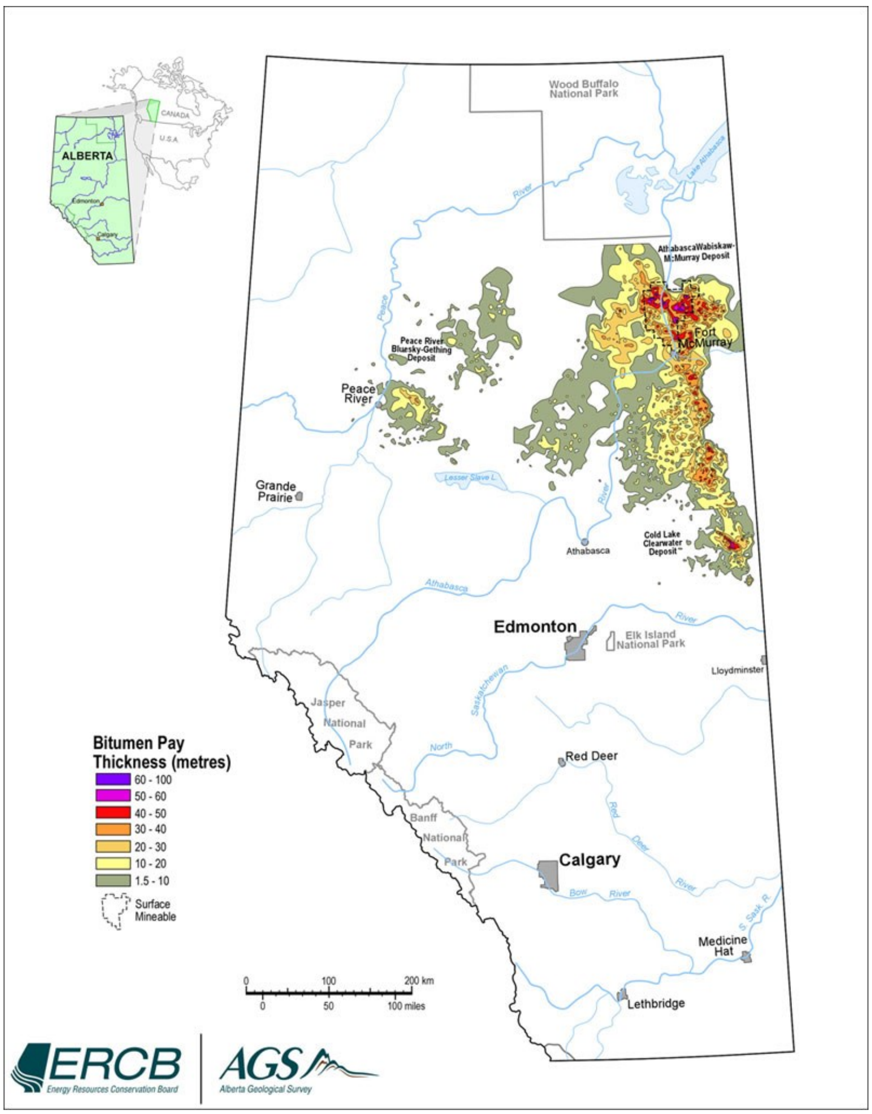

Figure 1. Oil Sands Deposits in Alberta (ERCB, 2012)

The relevant geology of the Athabasca oil sands deposit is generally comprised of the Upper Devonian Strata, overlain by the thicker Lower Cretaceous McMurray Formation. Surficial Quaternary deposits overly these formations. The geological units are summarized below and in Figure 2.

The Upper Devonian unit is mainly composed of limestone and calcareous shales. The contact between the Upper Devonian and Cretaceous McMurray Formations is an irregular surface (Morgenstern & Scott, 1997). Deep incised channels exist in the Upper Devonian with infilling composed of a variety of fluvial depositions and a fining upward trend of McMurray Formation sediments.

The Lower Cretaceous McMurray Formation generally consists of uncemented quartz sand and shales which has changed minimally post deposition. Oil sands deposits are in this formation, with bitumen content ranging between 10 to 18% (Morgenstern & Scott, 1997).

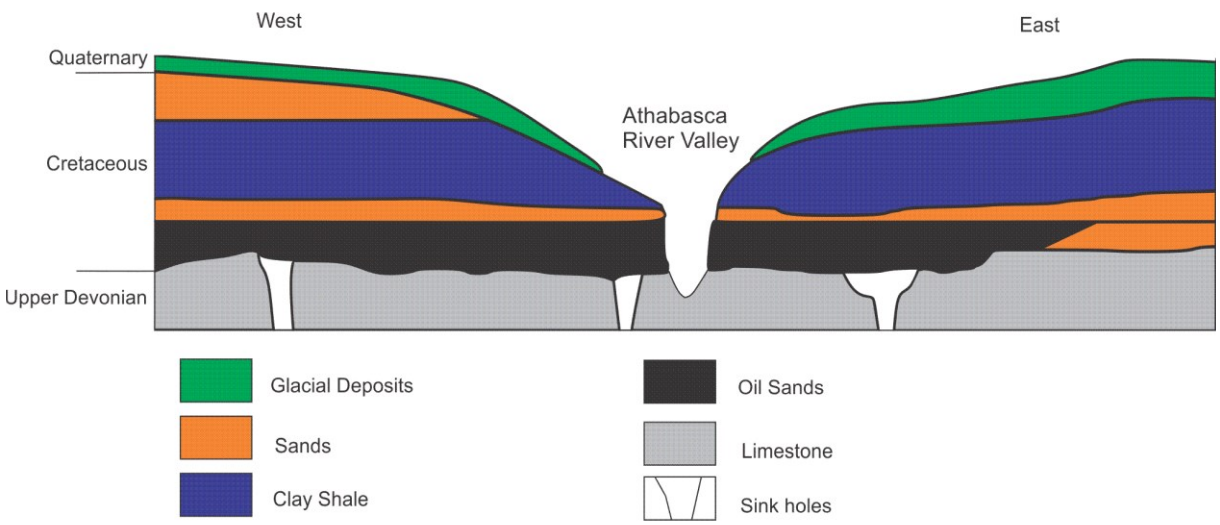

Figure 2. Simplified Oil Sands Stratigraphy (Carrigy & Mellon, 1959)

Above the McMurray Formation consists of Cretaceous clay shales and sandstone. The predominant formation is the Clearwater Formation, a heavily consolidated marine deposit composed of interbedded silty clay to clay shales (Martens & Charron, 2007). Layers of sand deposits are interspersed between the shale units. Pre-sheared zones and rafting due to glaciation are common in the Clearwater Formation (Bayliss et al., 2013). Layers of low density deposits and high pore pressure are frequently present within the formation, which result in significant geotechnical challenges (Martens & Charron, 2007). A sandstone unit identified as the Grand Rapids Formation generally overlies the Clearwater Formation (Flach, 1984).

Quaternary Pleistocene deposits, overlain by Holocene deposits rest on top of the Cretaceous units along a contact of erosional unconformity (Carrigy & Mellon, 1959). Pleistocene deposits are mostly the product of glacial deposition and typically consist of glacio-lacustrine silts and clays, glaciofluvial sands and gravels, commonly underlain by glacial tills of varying composition. The surficial Holocene soils are primarily composed of recent organic deposits and alluvial sand or clay deposits (Sisson et al., 2012).

The variability of the depositional sediments and non-conforming contacts between major units make it difficult to accurately predict stratigraphy over a scale larger than 50 m (Morgenstern & Scott, 1997). The resulting product is a complex geological setting with a range of geotechnical conditions.

2.2. The Mining Process

The following flow chart, Figure 3, summarizes the mining process in the oil sands with a range of waste streams that develop. Overburden, a broad term encompassing the natural deposits above an orebody, is removed to access the underlying oil sands. The ore is mined using a shovel and truck system to be transported to a crusher and subsequent bitumen extraction process. The resulting bitumen is diluted and shipped to market. The primary byproduct of bitumen extraction is tailings, the material waste after the economically and technically viable bitumen has been removed (McRoberts, 2008). The oil sands mining process produces multiple streams of material waste which must be managed. The management of these materials is discussed in Chapter 2.3. The management and storage methods of tailings is discussed in Chapter 2.4.

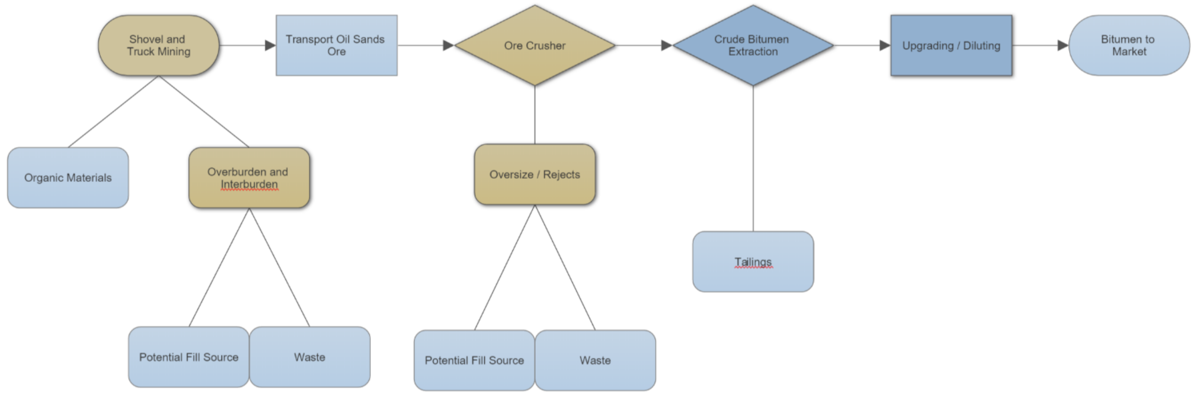

Figure 3. The oil sands process with associated waste streams

2.3. Waste Management

An oil sands mine's performance and environmental acceptability largely depends on the sound design and execution of waste management (Morgenstern et al., 1988). Waste management is significantly more critical in the early years of mine development where the open pit is not yet developed for in-pit tailings storage, therefore storage space is restricted to the external tailings facility. Volumetric waste to bitumen ratios may be on the order of 23:1 (Morgenstern et al., 1988), to give an indication of the volume of material that must be stored.

Thus, a mining plan with consideration for waste management is necessary to optimize production and handle waste streams (Morgenstern et al., 1988). The requirements of waste management can differ between mines due to the variability of site specific conditions such as geology and mine development techniques.

2.3.1. Waste Sources

The multiple waste streams that develop are shown in Figure 3. Stripping of surficial vegetation and organic materials is the initial source of waste and is typically stockpiled for future reclamation use. Overburden and interburden deposits are removed next; interburden is another broad term encompassing natural deposits between ore deposits. Due to the geological variability common to the region, it is possible to encounter up to 20 geologically different overburden soil types (Morgenstern et al., 1988), the majority of which are over-consolidated and fine grained.

As ore-grade oil sands is hauled to the plant for crushing and extraction, more waste streams develop. Feed rejects are removed as waste (Morgenstern et al., 1988). The tailings waste stream is produced during the bitumen extraction process, which is then stored in containment facilities as mentioned in Chapter 2.4.

Conventionally, non-tailings waste streams were disposed of in waste dumps (Morgenstern et al., 1988) which demanded a significant use of space and could reach heights up to 55 m. However, exploiting these waste streams as sources of fill for tailings dams provides a method of reducing the volume of material to be stored in waste dumps, while simultaneously providing a fill source for dam construction.

2.4. Tailings Management

The management of tailings is an elaborate process with many variables and discrepancies which vary between oil sand operators. It is regulated under the Oil Sands Conservation Act, which in part provides directives to manage fluid tailings (AER, 2017). Figure 4 shows a simplified tailings facility following the mining and extraction process.

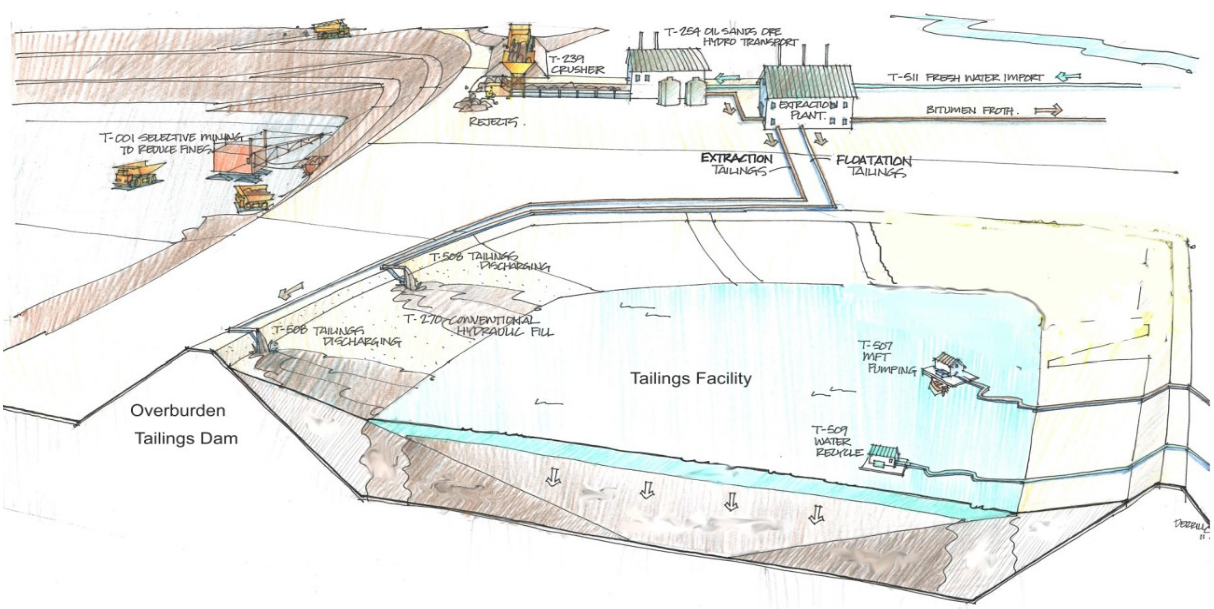

Figure 4. External tailings facility showing deposition and reclaim water storage following mining and extraction (Adapted from CTMC, 2012)

External tailings facilities may be used for the first 10 to 20 years of the mine life (Eshraghian & Becker, 2014), before in-pit tailings storage options become available. These external tailings facilities are commonly earth-fill dams situated over natural foundations. The natural topography does not typically provide sufficient confinement; thus, the earth-fill dams are commonly ring shaped.

As the open pit increases in size and areas of the ore body are depleted, the space can be utilized for tailings storage. Containment cells are formed with the construction of In-pit dykes founded on the pit floor and abutted against the pit wall or adjacent dykes (McRoberts, 2008). The pit floor can be hundreds of metres lower than the original ground surface, therefore in-pit dykes may be founded on entirely different geological units than external facilities.

2.4.1. Tailings Composition

Tailings are primarily composed of a complex combination of sands, silts and clays (fines), residual bitumen, chemical additives for process aids, and process affected water (McRoberts, 2008). The composition will vary by: (1) the local geological source, (2) the type of extraction processes used, and, (3) changes in operations and maintenance during extraction; such as necessary start-up and shut-down periods in the processing facilities. Due to the complex composition and variability of tailings, its geotechnical behaviour is difficult to predict.

2.4.2. Tailings Deposition

Generally, tailings are deposited as a slurry via pipelines. Segregation occurs upon deposition, where the coarser fraction of the tailings settles near the discharge point, forming a tailings beach (Morgenstern & Scott, 1997). The remaining fines flow further from the discharge point. The developed beach may be incorporated into the design of the dam and may serve as the foundation for future dam raises.

The remaining fines and residual sand which do not settle out collect in the pond as a sludge (McRoberts, 2008). This form of deposition has large storage volume requirements due to the amount of water required to transport and is subsequently entrapped as a sludge.

2.4.3. Water Management

Tailings containment facilities may be used to retain significant volumes of recycle water to be used for bitumen extraction. These facilities may also provide storage for non-releasable water. This includes water that has been in contact with oil sands, seepage collection, drainage and waste run off that cannot be released off site and thus need to be stored (McRoberts, 2008).

2.5. Defining the Oil Sands Overburden Tailings Dam

The physical impoundment of tailings is provided by the tailings dam. While different types of tailings dams exist, the most common are overburden dams, tailings sand dams, or a combination of the two (Eshraghian & Becker, 2014). Overburden dams consist of earth-fills sourced from the mine and are constructed using heavy earth moving equipment. Hydraulically placed tailings sands and conventional tailings cell construction techniques are used to build tailings sand dams.

Tailings dams are generally constructed over the life of the mine, on the scale of ten to twenty years (Eshraghian & Becker, 2014). Dam raises are accomplished in stages with a frequency dependent on variables such as the tailings management plan, production, availability of fills and economic influences. Over the lifespan of a tailings dam, the design of the dam may undergo several iterations in response to changes to these variables.

Three types of dam raise construction methods are commonly implemented (Fell et al., 2005): upstream, downstream, and centerline, as shown in Figure 5. Upstream construction utilizes a starter dam to provide the initial impoundment and allow time for the development of an upstream tailings beach to form. The stability of this tailings beach is critical, as it is used as part of the foundation for future raises. Overburden fill dams are typically not constructed in an upstream fashion; however, the starter dam component may be constructed from overburden materials. For downstream construction, raises are built in the downstream direction from the starter dam, stepping out on in-situ foundation each time. As a result, the footprint of the dam increases with each raise. Centreline construction results in dam raises where the centerline of the dam does not change.

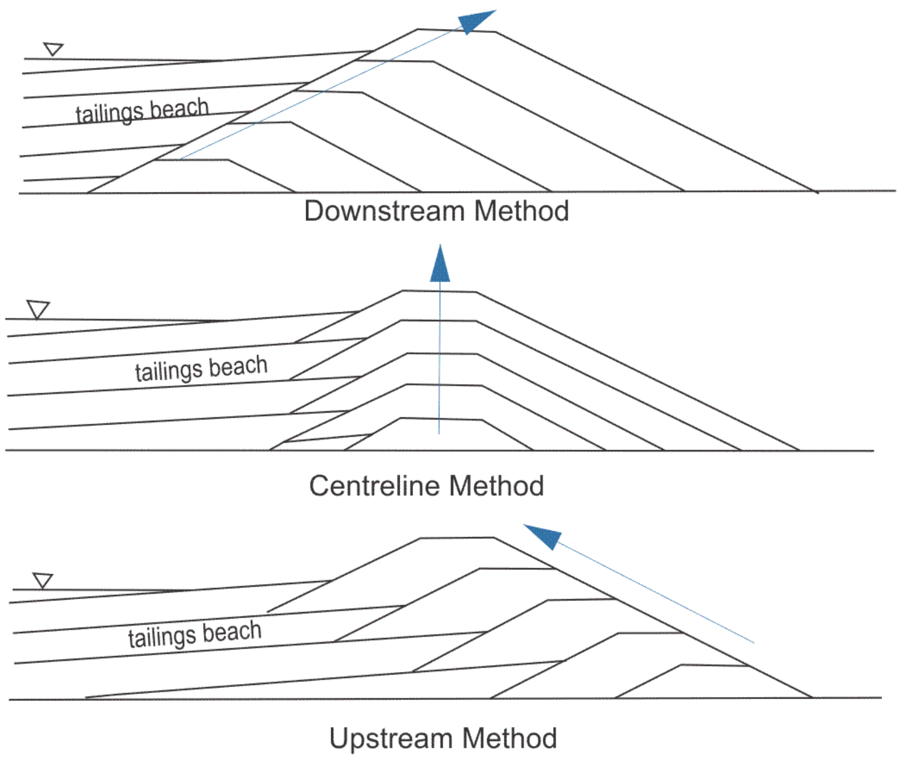

Figure 5. Upstream, downstream, and centreline construction methods. Arrows indicate direction of centreline movement (after Vick, 1990)

2.5.1. General Dam Cross Section

The design of an overburden tailings dam must take into consideration its expected use, topographic and foundation site conditions, and availability of materials. As every site differs, several types of earth dams exist with varying degrees of purpose and built in conservatism (Fell et al., 2005).

The strategic placement of materials within a dam cross section based on their geotechnical behavior is a common practice to satisfy dam safety criteria and utilize locally available fills (Eshraghian & Becker, 2014). These zoned dams are statistically a safer type of dam compared to other types, such as homogeneous dams (Fell et al., 2005), by providing multiple lines of defense to manage seepage and internal erosion. An example of a simple zoned dam is shown in Figure 6.

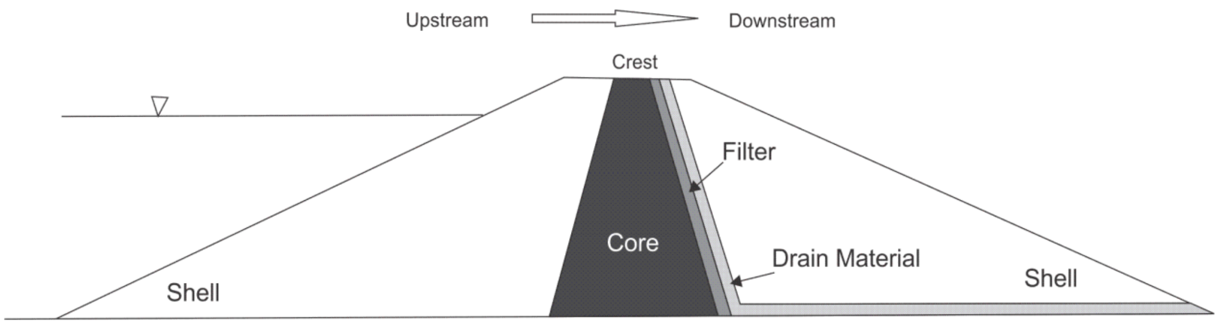

Figure 6. A simple zoned dam (after Vick, 1990)

Seepage is primarily controlled with the use of a low permeability fill, such as clays and silts, as the core zone of the dam. Filter and drain zones usually consist of engineered sands and gravel and are typically located adjacent to the core (Fell et al., 2005). They serve three main functions: (1) control erosion of the core, (2) allow for the dissipation of pore pressures, and (3) provide a discharge point for seepage. Upstream and downstream shells provide stability and erosion protection for the internal fill zones.

Oil sands tailings dams may use a variety of locally available materials as dam fill, including: overburden, interburden, lean (low bitumen content) oil sands, clay shales, and tailings sands. The materials are placed according to their geotechnical behavior and capability of satisfying the design criteria of each zone in the dam.

2.5.1.1. Zoned Fills Criteria

Design criteria is established for each fill zone of the dam based on the available materials and their intended function in the dam. A general overview of these criteria is described below (U.S Department of the Interior Bureau of Reclamation., 1998).

Low permeability fills typically must satisfy the following criteria:

- Be of a sufficiently low permeability to restrict the excessive flow of water
- Form a homogenous mass free of defects or potential seepage paths
- Resist excessive consolidation and differential settlement due to saturation or superimposed loads
- Achieve and maintain the intended shear strength

Pervious fills are typically used as filter or drain materials in a dam and generally must satisfy the following criteria:

- Homogeneous to allow even distribution of seepage flows
- Be sufficiently permeable for its intended function
- Resist excessive consolidation and differential settlement due to saturation or superimposed loads
- Maintain a high angle of internal friction
- Provide appropriate grainsize compatibility internally and with adjacent materials

Conventional dam construction often relies on rock fill for the construction of the upstream or downstream shells (Fell et al., 2005). As rock fill is not easily available within the oil sands region, the shell of a tailings dam may instead consist of more readily available overburden or interburden soils. Achieving a high density and providing stability for the structure is the primary design function, while drains consisting of pervious fill or pipes are incorporated to promote drainage of seepage through the shell and to mitigate pore pressure development.

For downstream areas of a dam that may be less critical to design, such as a toe berm, an increased variability in fill may be tolerable. When handling variable or miscellaneous fills, the control of excessive settlement is a primary concern for fill selection (U.S Department of the Interior Bureau of Reclamation., 1998).

2.6. Balancing Operational, Technical, and Economical Needs

The design of a tailings dam is a function of the demands of mine operations, tailings management and available materials, (McRoberts, 2008) in conjunction with safe geotechnical criteria. The mine and tailings plans are continually updated over the life of a mine in response to changing conditions, both geological and economical. The result is an iterative and interactive process, where each component influences each other as expressed in Figure 7. Effective communication between the invested parties becomes a critical aspect of facilitating the process.

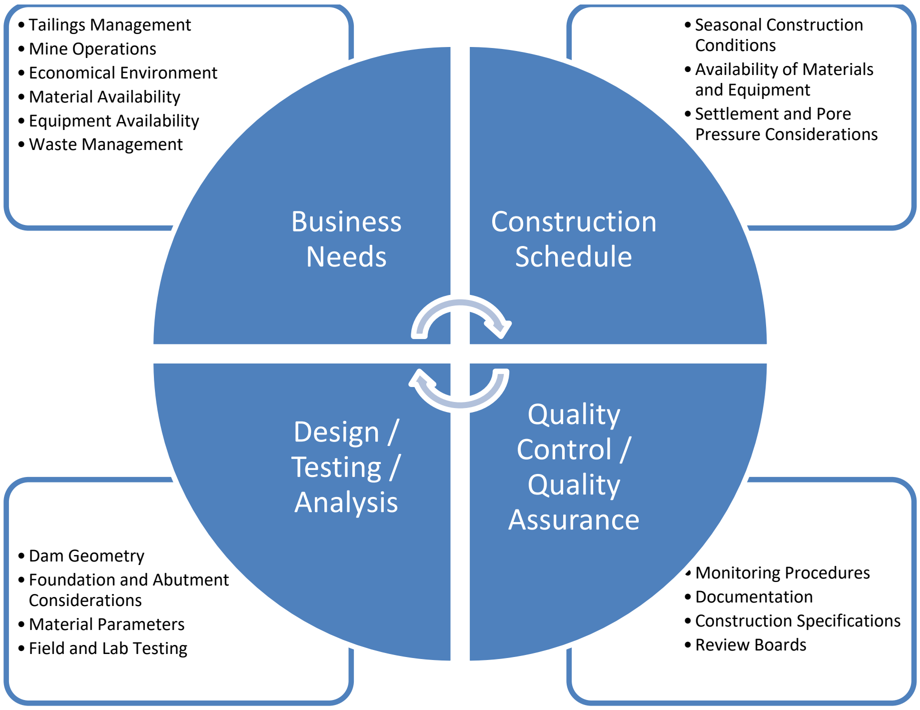

Figure 7. Interaction of Business, Operational, and Technical Needs (after Cameron, 2013)

While this approach is not new to dam construction, the daily quantities of materials moved and the resulting size of the structures are unique to the oil sands industry (Morgenstern et al., 1988). Oil sands dams may be constructed on the scale of 25Mm^3/year, in a challenging northern climate (Cameron, 2013). As a result, design and construction goals have evolved over the last few decades in response to the economic demands of an oil sands mine, climate conditions, operational constraints, and the availability of fill types. An example of this evolution in the oil sands can be seen in Suncor's first dyke composed of overburden fills, the East-West Dyke.

The East-West Dyke was constructed over a span of 12 years, starting in 1971, but with construction limited by in-pit activities until 1979. The structure was scheduled for completion in 1982. The initial design relied on a conventional dam design approach, with steep slopes and high strength fills (Morgenstern et al., 1988). An internal clay core provided seepage control along with a downstream sand filter, as shown in Figure 8. Sand roads were built in the upstream and downstream zones for controlling pore pressures in the fill and machine accessibility for the expected difficult trafficability on the overburden fills (McRoberts, 2005).

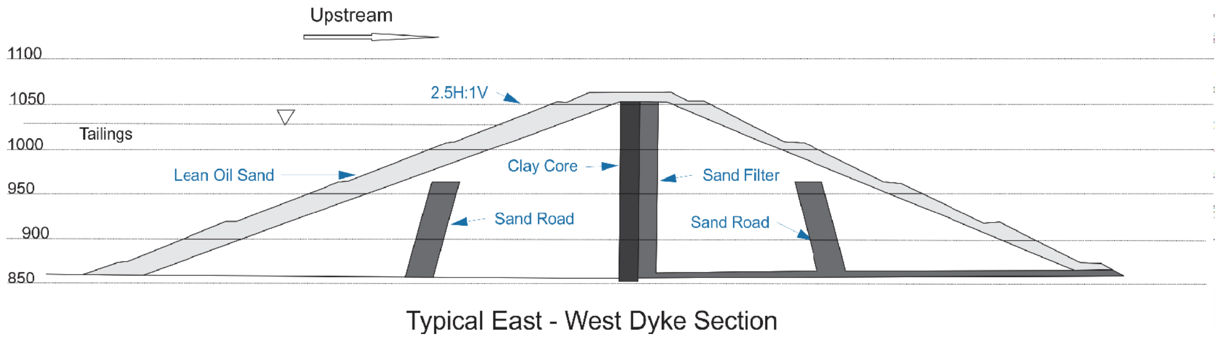

Figure 8. Suncor East-West Dyke Original Design (after McRoberts, 2005)

However, a combination of wet fills, poor trafficability, and foundation conditions created a concern for stability which was amplified by a slope failure on an adjacent dyke in 1974. The slopes of the East-West dyke were first shallowed to 3H:1V, then subsequently to 3.5H:1V once further cracking and a slope failure was observed in 1977 and 1979, respectively. (Morgenstern et al., 1988),

A redesign utilizing the 3.5H:1V slopes included a series of downstream horizontal sand drains, see Figure 9, were incorporated to accommodate wet fills and pore pressure generation due to the increased rate of fill placement to meet the construction schedule. Tailings sand beaches on the upstream face provided a secondary line of defense for internal stability. More rigorous quality controls on fill materials and construction methods were applied. Simultaneously, performance studies in the winter of 1981/1982 approved the use of winter construction to meet the construction schedule and optimize equipment use. The structure was completed in 1983.

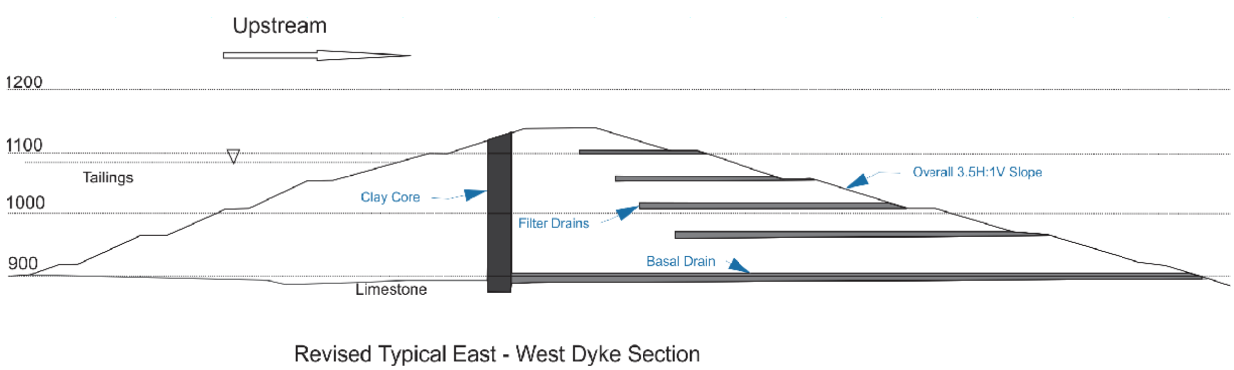

Figure 9. Redesign of Suncor East – West Dyke (after McRoberts, 2005)

The restrained construction schedule played a critical role in driving innovation, specifically the development of winter construction methods. The difficult foundation conditions in the local geology and variable, typically wet, fills required an adaptable design, in this case utilizing the use of broader slopes with drains. Tighter quality control measures were necessary to satisfy that the design criteria were met under the construction conditions.

Tailings dam design is intrinsically tied to the overall business plan of an oil sands mine (McRoberts, 2005). The size of dams has increased to match the increasing production of the past few decades and its corresponding waste management needs. Design iterations are necessary to adapt to accommodate mine planning over the possibly decades long life of a tailings dam as the availability of fills changes as operations within the pit progress and tailings production develops. Designs must be robust and consider the potential for future design revisions in response to changing conditions.

2.7. Common Design Considerations

Geotechnical hazards relevant to an oil sands tailings dam may be summarized into the following categories (Eshraghian & Becker, 2014), (Fell et al., 2005): overtopping, slope stability, internal seepage and erosion. These topics are summarized below as they relate to oil sands tailings dams.

2.7.1. Overtopping

As oil sands dams do not have mechanisms to release water, the tailings pond must be constructed and sequentially raised to a sufficient height to provide the necessary storage volume for precipitation events. CDA guidelines require that a minimum freeboard be established for a dam, that must withstand the Inflow Design Flood (CDA, 2007). Differential settlement of the dam or underlying foundation may also be a cause of an overtopping failure.

2.7.2. Slope Stability

Tailings dams pose a unique challenge to stability analyses due to their long construction periods. Incremental increases to the loading conditions and corresponding increase in risk are a by-product of each dam raise.

Conventional loading conditions such as rapid drawdown and seismicity are not as relevant to oil sands dams. There are no release mechanisms in an oil sands dam, thus the only scenario in which a rapid drawdown occurs is during dam failure. The Fort McMurray region is an area of low seismicity and thus the seismic condition is considered a very low probability (Eshraghian & Becker, 2014). The main categories for loading conditions that apply to the oil sands are the end of construction and long-term scenarios:

End of Construction

During and upon completion of construction and operations, pore pressures in both the foundation and fills are at their most critical. Liquefaction may be a risk depending on tailings depositional conditions (Eshraghian & Becker, 2014). A common design method is to construct the dam with sufficient width to withstand the load induced by static liquefaction of the contained tailings beach (McRoberts, 2005).

Long-Term

Long term conditions are achieved when seepage reaches a steady state at a normal reservoir level (Eshraghian & Becker, 2014). As a tailings dam reaches its final crest elevation, tailings deposition gradually declines and the phreatic surface in the dam lowers. Common practice then is to estimate the post operational phreatic surface to assess the long-term stability of the structure.

Foundation conditions and pore pressure generation are two factors that impact slope stability for tailings dams, as discussed below.

2.7.2.1. Foundation Conditions

Foundation conditions are dependent on lease geology and have a wide range of geological behaviours dependent on location (McRoberts, 2008). Each lease has a unique geology, and these conditions may be variable within the lease as well. The range of geological units encountered may include weak to competent materials in each formation with varying thicknesses and degrees of consolidation.

Of significance, the Clearwater Formation contains an abundance of clay shales which are sometimes present in the McMurray Formation. These clay shales can be problematic as they contain pre-sheared zones and slickensides. The friction angle in these pre-sheared zones are on the range of 7 to 8° (Martens & Charron, 2007), and often govern the stability of the overlying structures. The pore pressure response in these clay shales can be highly variable, requiring a conservative or observational approach for design (McRoberts, 2005). Leases which encounter the Clearwater Formation may need to design dam slopes as shallow as 17-20H: 1V to provide a sufficient factor of safety (McRoberts, 2008).

2.7.2.2. Pore Pressure Generation

Achieving a high density is desirable for impervious fills to manage consolidation, softening, and stability. However, the generation of pore pressures is a by-product of densification by compaction (U.S Department of the Interior Bureau of Reclamation., 1998). An increase in pore pressure creates a reduction in shear strength of the soil, which in turn can influence the global stability of the structure. Thus, control over pore pressures during construction is an important aspect of construction.

The magnitude of the pore pressure generation during construction is influenced by the following five factors: (1) fill height and permeability, (2) degree of compaction, (3) rate of construction, (4) fill water content, and (5) drainage conditions. Four case studies exploring the impact of the above listed factors can be found in Cameron et al. (2001), Li (1967), Matheson et al. (1987), and Seto et al. (2009).

In the realm of oil sands tailings dam construction, structures are built to an immense size and require a rapid rate of construction necessary to maintain the schedule set by operations. The variability of fill materials leads to difficulty in accurately predicting pore pressure response. In addition, the compaction of fills is commonly achieved with loaded haul trucks providing a degree of compaction substantially greater than conventional compactive equipment (McRoberts, 2008).

Designers may increase their conservatism in design to accommodate for pore pressure generation, with the use of shallower slopes for stability and provide drainage measures to promote the dissipation of pore pressures. Where appropriate, the observational method (Peck, 1969) may be used to implement a less conservative design, provided sufficient monitoring and corrective strategies are in place, and the failure mode is not a brittle mechanism.

While moisture conditioning of fills during construction is not feasible due the large volumes, being selective of the source materials used can minimize the volume of wet or soft soils that may promote pore pressure generation once compacted in the structure. While most overburden fills in the region are naturally dry of optimum (McRoberts, 2005), a balance is necessary, as fill that is too dry may not densify as effectively, and be prone to hydraulic fracturing (Cameron et al., 2008).

2.7.3. Piping and Internal Erosion

Piping or internal erosion is the most common form of failure in embankment dams (Fell et al., 2005). The presence of defects in fill are a primary cause of internal erosion (McRoberts, 2008). The source of these defects can stem from several sources, including the following: (1) hydraulic fracturing, (2) differential settlement, (3) poor compaction or poor-quality fill between lifts, (4) poor compaction of fills against foundation abutments.

The application of a zoned dam cross section, specifically the use of appropriately graded filters is the first line of defense against internal erosion (Fell et al., 2005). Filter zones and chimney drains serve to intercept seepage along a crack or defect in the core. The cohesion less nature of the filter restricts further crack. The filter must be graded in such a manner to prevent the migration of particles between adjacent material types, whether fills or in-situ foundation soils. Seepage collected within the filters then collects and drains downstream through an offtake system such as horizontal drains.

Homogeneous dams are vulnerable to internal erosion to occur as they lack the presence of filter materials to restrict crack propagation along a defect in the fill. Syncrude’s homogeneous Highway Berm partially mitigated this risk by overbuilding the dam to significantly increase the overburden stress and extend the seepage length, thereby reducing the potential for hydraulic fracture (Cameron et al., 1995). Additional precautionary measures included tight quality control and supervision over fill placement and the relatively short ten-year design life.

2.8. Specifications

To satisfy that the construction process achieves criteria set by design, specifications are developed as part of a contract between the contractor and owner. Specifications, along with construction drawings provide a schedule of work and set of requirements which must be satisfied by the contractor.

The assumptions, confidence, and uncertainty of design should be incorporated into the development of specifications (U.S Department of the Interior Bureau of Reclamation., 1998). This allows the contractor to understand the design intent and expectations of construction. While specifications encompass all aspects of the work necessary for the project, the focus of this thesis is on sourcing and placement of fills with the necessary quality controls.

Specifications can be grouped into two types, (1) performance based requirements or (2) method based requirements. A performance based specification describes the product to be achieved through construction. Typically, the contractor is responsible for the selection of materials, equipment used, and construction methods. The criteria that may be stipulated for a performance specification includes the following (Fell et al., 2005):

- Particle size distribution
- Atterberg limits
- Density ratio
- Moisture content

The desirability of a performance based specification is understandable, however limitations in the understanding of soil mechanics and variability of available fills can cause further complexity of the specifications. Extensive testing, experience, literature, and statistical data are also used to define the upper and lower bounds of properties for fill specifications. Defining appropriate specifications which accurately represent the fill materials and site conditions may make this type prohibitively expensive and complex (U.S Department of the Interior Bureau of Reclamation., 1998).

A method specification describes how construction is to be conducted to achieve the desired outcome (Fell et al., 2005). The construction procedures, equipment, and materials used may all be specified, including the following:

- Material sources
- Moisture content
- Lift thickness

- Type and weight of compactive equipment
- Number of passes with compactive equipment

Earth-fill dam construction often applies a combination of the two alternatives; a minimum procedural requirement and performance or vice versa (Fell et al., 2005). The balance between the two alternatives may vary between projects due to variables such as site conditions and the relationships between the owner and contractor.

2.8.1. Test Fills

Where limited information or variability pose difficulty in the selection of appropriate control parameters, empirical techniques may be used to determine optimal lift thicknesses, compaction methods and test methods. One such empirical technique is the use of test fills. The purpose of a test fill is to determine the optimized process for construction activities such as placement and compaction (U.S Department of the Interior Bureau of Reclamation., 1998). The outcome of a test fill will aid in determining appropriate specifications and quality control measures to support construction.

A test fill functions by performing a trial version of the intended construction activity at a small scale, while altering variables such as lift thickness, rate of placement, number of passes and type of equipment. The trial is followed by a comprehensive investigation in geotechnical properties and the observations of the fills performance in the trial. The purpose of this investigation is to determine the optimal parameters and methodology for the construction activity. Multiple test fills may be performed to evaluate the impact of each altered variable.

In a conventional dam construction setting, test fills may also be used to evaluate the foundation response to the loading of fill material, which may in turn govern the rate of fill placement. These test fills may incorporate instruments to assess settlement, pore pressure response, loading conditions and mobilization (Rowe et al, 2001). Conducting a test fill of this sort can be time costly and not conducive to a tight construction schedule, therefore the practicality of performing one should to be evaluated considering the technical and production risks to the project.

Generally, test fills used to evaluate a potential borrow material are conducted on a sufficiently wide enough area to be considered representative of typical construction conditions. The fill is placed, and the number of passes completed by the haul truck is noted. Rut and roll observations are closely documented (G. Ferris, personal communication, September 4, 2015). Figure 10 provides an example of the layout for a test fill to evaluate a potential construction fill.

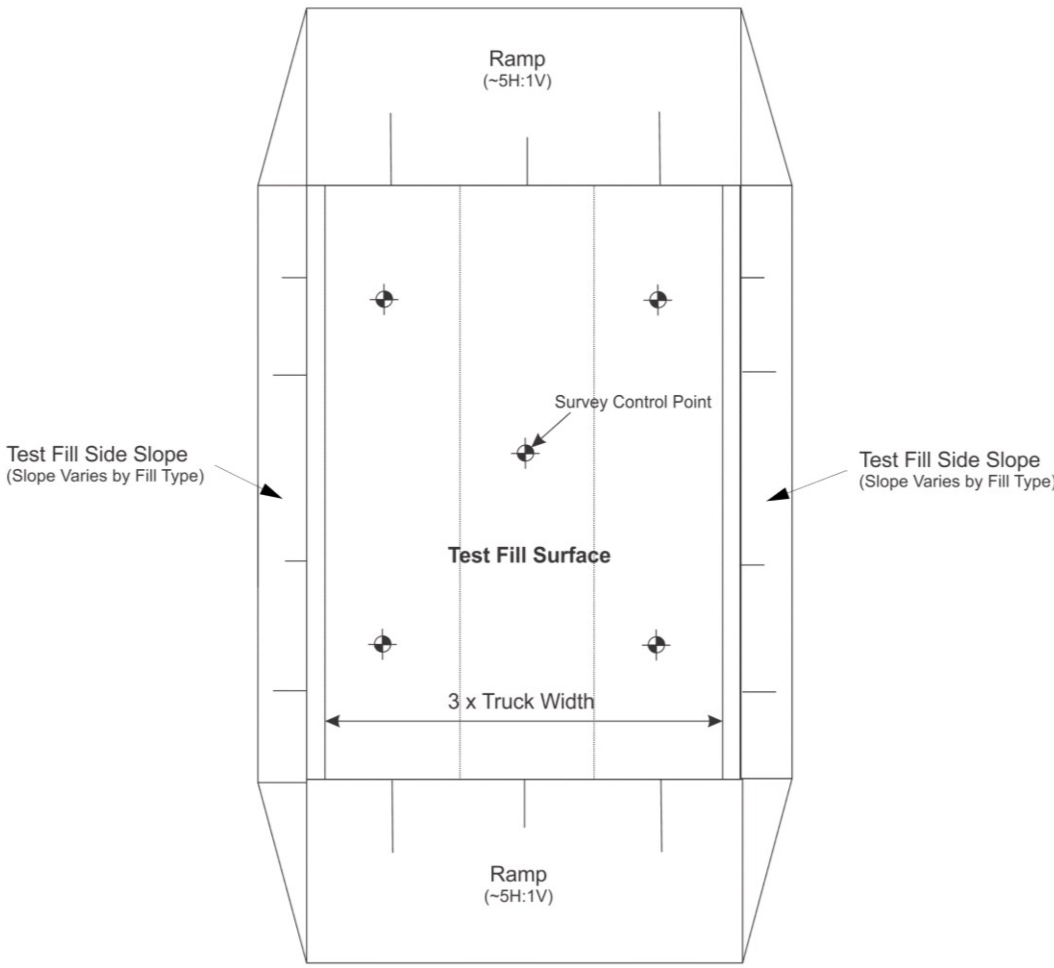

Figure 10. Test Fill Layout (after Breitenbach, 1993)

Following compaction, density tests and sampling are performed at surface and at depth to evaluate the degree of compaction with lift thickness. Testing at depth is performed via test pits. The test pits can be dug in stages, such as 0.5m depth intervals. Thorough visual observations to evaluate the soil structure, degree of compaction, presence of layering, and the size of intact blocks should be evaluated. Index testing and sampling can be performed along the test pit wall and in-situ samples can be collected for lab testing to supplement the in-situ density tests

In fills which must satisfy permeability criteria, in-situ permeability tests can be performed within the same test pits dug into the test fills. A relatively simple test, the test pit is filled with water and a falling head test performed (Cameron, 2013).

Once placement procedures have been established, large scale construction will commence, with operations following these procedures. If materials or site conditions change, a new test fill or performance assessment may be necessary to satisfy that the desired performance is still being achieved under new conditions.

Specific to the oil sands, a limited amount of literature is available on compaction with the use of haul trucks as compared to conventional methods. This uncertainty, combined with the variability of fills encountered in the oil sands necessitates the use of test fills to determine the optimal thickness of lifts and number of passes to achieve the desired design criteria.

2.9. Quality Control

The quality of construction is assessed by observations, measurements and testing. The primary functions of quality control can generally be summarized as follows (U.S Department of the Interior Bureau of Reclamation., 1998):

- Satisfy that the structure meets the goals of design and specifications
- Observe and document construction activities for record keeping
- Monitor and adapt to changing conditions
- Verify the works completed
- Test for compliance and performance as per design requirements.

Quality controls can be viewed as the measures put in place to satisfy that the specifications are being met. Thus, the quality control measures implemented will be heavily influenced by the types of specifications implemented. As discussed in Chapter 2.8, performance based specifications will rely heavily on sampling and testing to confirm that the geotechnical properties of the in-place fills meet the specified criteria. Method based specifications instead rely on a more qualitative approach, such as monitoring the placement and compaction methods and satisfying that the appropriate number of passes were achieved. Ideally, a balance is maintained between the two methods.

2.9.1. Inspections

Earthworks construction relies on the use of locally available soils with a range of geotechnical properties. This variability necessitates a steady presence of qualified quality control personnel to undertake the necessary observations, testing and documentation. The presence of quality control personnel provides an opportunity to evaluate the actual conditions and reflect that back to the design team. Inspection personnel are typically required in the following locations (U.S Department of the Interior Bureau of Reclamation., 1998):

- Borrow areas
- Areas of excavation and foundation preparation
- Zones of fill placement and compaction
- Dispatch for transporting fills

Inspections should be performed by qualified personnel who have the technical expertise and experience in their fields to accurately assess field conditions. A thorough understanding of the design and its intent is critical (U.S Department of the Interior Bureau of Reclamation., 1998).

The frequency of inspections will vary on the type of work being performed, variability of materials and intended function of the material. If works are critical and operating on a 24/7 schedule, the performance of quality control inspections must match that schedule.

Inspections may consist of the following duties:

- Confirming excavations or fill placement has been completed to the design limits;
- Assessing foundation and lift conditions are suitable for fill placement;
- Observing construction methods are consistent with requirements;
- Visual classification of soil characteristics in both in-situ and placed fills;
- Perform testing and sampling as necessary, such as rut and roll measurements, test pitting, or density testing;
- Measure and document all activities;

Maintaining consistency between inspectors is a challenge due to the qualitative approach to inspections. Standardizing the evaluation criteria that inspection personnel will apply enables a consistent and repeatable approach.

For example, Syncrude's Highway Berm addressed variability in its quality control teams by developing systems of standardized classifications, terms, and descriptions for the specific fill zones. These systems were modified to handle seasonal changes in site conditions. Directions were provided on how to perform rudimentary field tests to assess performance in a consistent manner. The quality control criteria were deemed non-negotiable between the monitoring staff and mining operations and could only be altered by the design engineer (Cameron et al., 2001).

2.9.2. Materials Testing

The testing of materials is used to classify and determine the material properties. Sufficient testing helps identify differences between acceptable and unacceptable works or materials as defined by the specifications (U.S Department of the Interior Bureau of Reclamation., 1998). Relationships established between the geotechnical properties such as shear strength, moisture content, and density are used along with visual observations of soil characteristics to supplement information collected via testing.

Index testing such as grain size distribution and Atterberg Limits are conducted to classify the soil and satisfy that it meets design criteria. A suite of additional test measures can be performed to evaluate the suitability of fills for the desired function, such as dispersivity in fine grained soils or soundness for granular fills. Standards for most test methods are provided by governing bodies such as the American Society for Testing and Materials (ASTM).

To measure the degree of compaction achieved, maximum dry density is commonly used (Das, 2005). Field tests such as nuclear densometers are performed on compacted lifts to measure the in-situ moisture content and maximum dry density. The results are compared against laboratory determined values based on Proctor tests performed on sufficiently representative soil samples.

Two types of Proctor Tests are commonly used, standard (ASTM D698) and modified (ASTM D1557) methods. The purpose of the modified Proctor test was an attempt to represent heavier compactive equipment. Figure 11 shows as the compaction effort is increased, the maximum dry unit weight is increased, while the optimum moisture content is decreased, albeit not proportionally (Das, 2005).

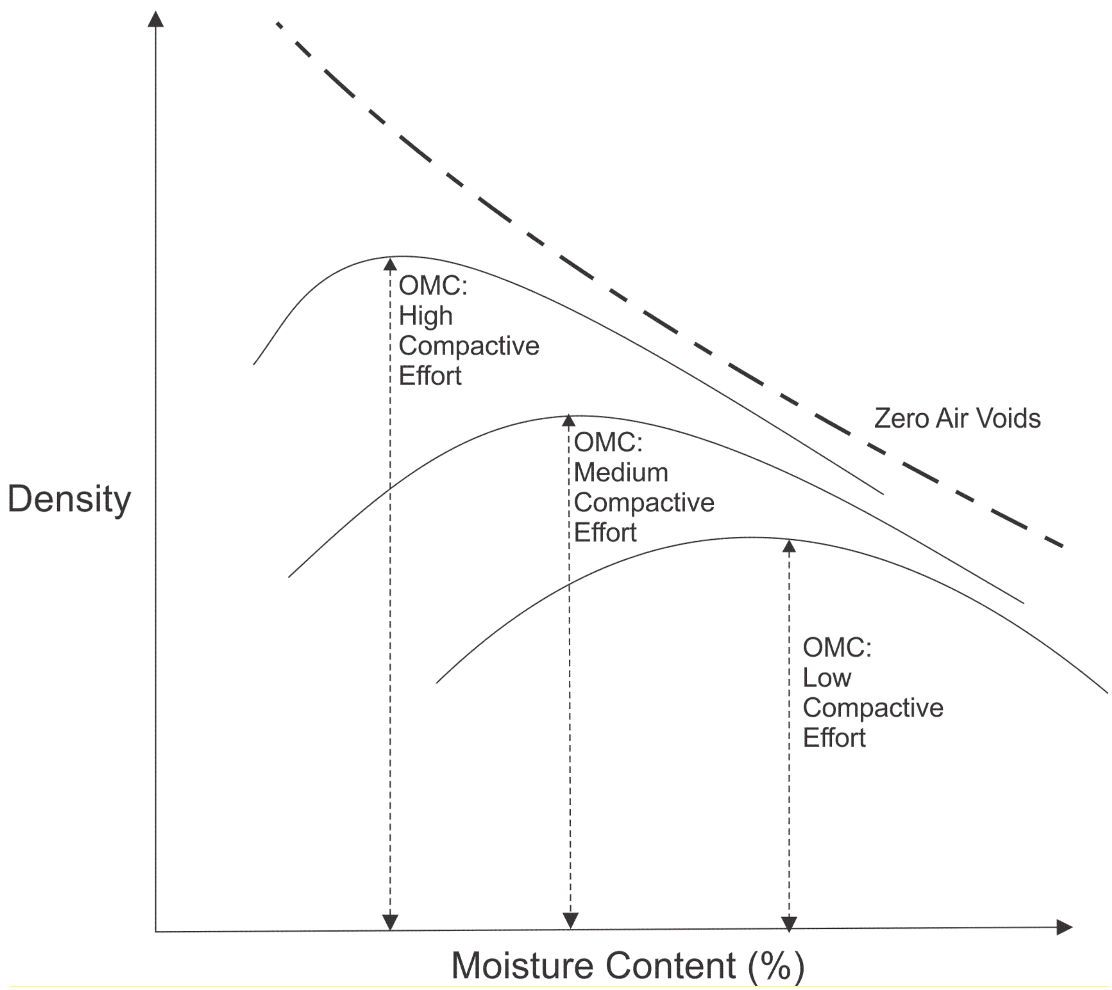

Figure 11. Influence of compactive effort on compaction curves (after Thompson, 2011)

However, (Fell et al., 2005) recommends that the Standard Proctor Test be used for dam construction. This method was also used at Syncrude's Highway Berm (Cameron et al., 2001) and for in-pit dyke construction at Shell's Albian Sands (Seto et al., 2009). The use of the Standard Proctor Test allows for moist compaction, which promotes flexible fills with low permeability. Higher densities are achieved under modified compaction; however, the fill may be more prone to increased permeability, and brittle behaviour.

(Fell et al., 2005) recommends a density ratio of greater than 98% of the standard maximum dry density be specified for fine grained soil compaction in dams. An optimum water content is typically specified within a range based on the properties of the available fill types and subject to site specific conditions. A higher density ratio may require compaction with soils dry of optimum, however, this increases the soils potential for erodibility (Fell et al., 2005). In wetter climates where higher moisture contents are unavoidable, a lower density ratio of 95% may be specified under the provision that compaction be carried out with a moisture content greater than optimum. Caution is necessary under these conditions; if a low-density ratio is achieved and the moisture content is less than optimum, a permeable soil structure may be formed (Fell et al., 2005).

2.9.3. Field Testing

Rut and roll testing to evaluate compaction performance is an example of providing quality control in accordance with a method based specifications. This type of test involves driving a specified piece of equipment such as a loaded haul truck over the area to be evaluated and measuring the deflection in the ruts compared to the ground surface, as depicted in Figure 12. The roll refers to a 'wave' of material that may develop in front of the tire as it progresses through the area. Rutting and rolling is an indicator that the tested area may not be fully compacted, that the material that may be too wet, and can give an indication of plasticity.

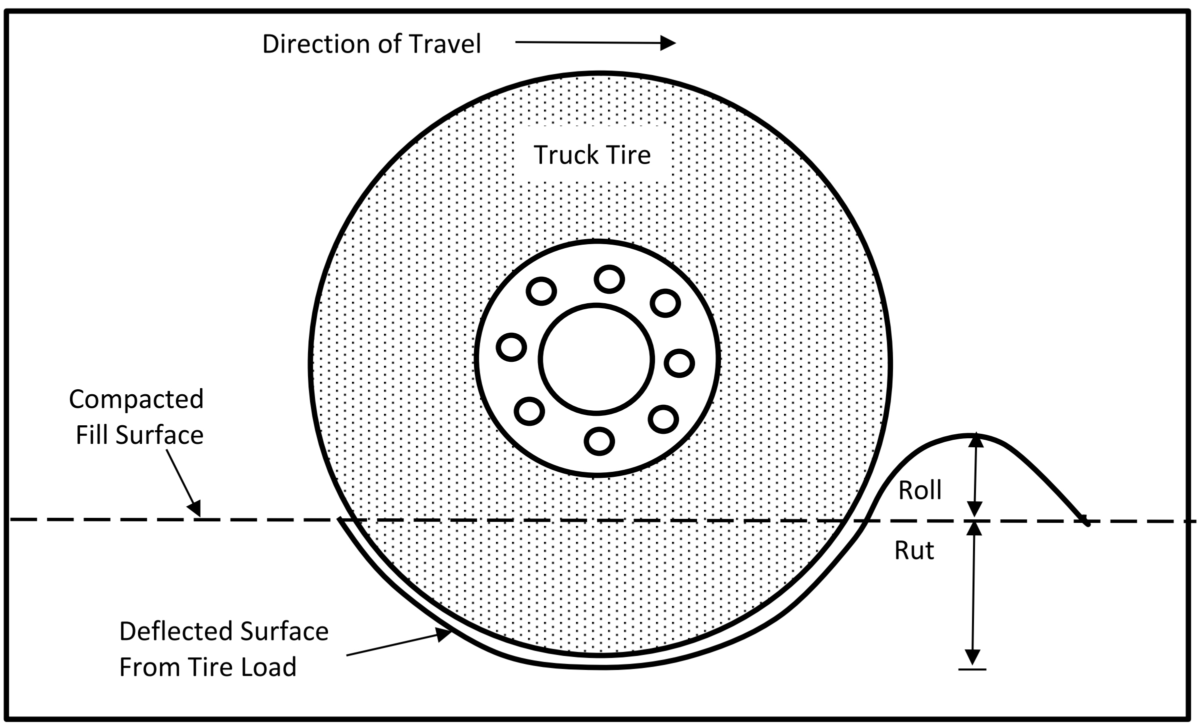

Figure 12. Rut and Roll Schematic

A combination of the performance and methodology quality controls were implemented for the Syncrude Highway Berm. Monitors would observe the placement and compaction of fills and document the results of rut and roll testing. A maximum differential of 0.3 m, or one half the lift thickness was applied as rut and roll criteria for the Syncrude Highway Berm (Ashton & Cameron, 1995). At Shell's Albian Sands, rut and roll criteria ranged from a maximum differential of 50 mm to 100 mm when travelled with a 400 Ton haul truck, depending on material type (Seto et al., 2009).

Following the completion of a compacted lift, density testing and sampling was conducted. Density tests were performed at multiple depths through a lift; the effective range of a nuclear densometer is typically 0.3 m deep, thus more tests are necessary for a 1 m thick lift. This was accomplished with a dozer cutting into the compacted lift in intervals for the testing (Ashton & Cameron, 1995). The test pit can be remediated by backfilling the excavation and recompacting with haul trucks.

2.9.3.1. Test Pits

Test pits can be dug into lifts to provide a visual assessment of compacted fills and collect samples at multiple depths within a lift. Exposing the compacted fill in a lift via a test pit allows the homogeneity of the lift to be evaluated, along with the degree of compaction through the entire thickness of the lift. Samples and in-situ testing can be performed through multiple depths within the lift during and after excavation.

A general procedure for a test pit excavated into fill can be considered as follows (G. Ferris, personal communication, September 4, 2015): A test pit is dug approximately 1 m or greater, depending on the lift thickness. The excavation should be sloped as necessary to ensure safe ingress and egress for personnel. Extending the depth of the test pit into the existing lift is preferable to evaluate the contact between lifts.

The test pit can be dug in stages, approximately 0.3 m or 0.5 m thick layers at a time, to permit sampling and testing on the surface of the test pit floor at each depth interval. The in-situ testing types may include density and shear strength tests. Samples may be collected to evaluate the gradation, bitumen content, and moisture content. Samples could be taken along the test pit wall to develop a profile of properties versus depth.

While open, the walls of the test pit should be visually inspected to evaluate homogeneity and uniform compaction across the entire lift and the underlying lift. If anomalies or undesirable conditions observed, undisturbed samples or bulk samples could be collected for further testing.

At both Syncrude' Highway Berm and Shell's Albian Sands in-pit dykes, test pits were conducted in completed lifts. These test pits were used to evaluate the condition of placed fills over multiple lifts and verify that a sufficiently compacted and homogenous unit of fill has been formed through the entire lift. Permeability of the soil could be empirically assessed by filling the test pits with water and monitoring the time required for the water to drain into the fill (Cameron, 2013). Samples and in-situ testing were conducted in conjunction with documentation of the observations.

2.9.4. Testing Frequency

The frequency of testing required is determined by the number of tests necessary to provide an accurate representation of the materials placed (U.S Department of the Interior Bureau of Reclamation., 1998). This frequency depends on the material type, quantity of material, function and the sampling procedures. The frequency may be measured by volume, such as requiring a test every 2000 m^3, or by area, for example a test must be performed every 70 m by 70 m area. Samples will be taken for lab analysis and testing to support and calibrate the accuracy of the field tests.

Another technique is to focus testing frequency on areas of poor performance (Fell et al., 2005). This technique operates on the assumption that if the worst part of a lift passes, the entire lift passes, which may result in fewer tests being required than a defined frequency. However, this results in biased sampling and testing methods. Sufficient documentation is necessary for whichever testing frequency method is selected for consistency and accuracy.

The overall quality of the dam can be evaluated by statistical analysis of test results. Compiling and assessing the test data will identify trends which can be used to predict future conditions or identify areas of concern that must be addressed. Performing testing on a minimum frequency facilitates developing statistical limits on testing. When managing large quantities of fill, sufficient test data may show that the failure of a small percentage of placed materials will not affect the overall performance of the structure (Fell et al., 2005).

2.9.4.1. Testing of Large Volumes

When attempting to place large volumes of fill with significant variability, such as that encountered in the oil sands, accurately representing the placed fills through testing is a challenge. Syncrude's Highway Berm addressed this problem by grouping together fills that had generally similar behavior and properties (Ashton & Cameron, 1995). Four categories were developed based on their maximum dry density. Placed materials were categorized based on their source location, visual indicators, and geotechnical properties. Testing performed on these materials were then compared against the representative properties of that category.

Alternatively, a minimum compacted dry density may be applied. This method was applied at Shell's Albian Sands in-pit dykes. A minimum dry density was specified for the designed fill types, i.e. 1700 kg/m^3 for Type 1 fill; identified as a 'good quality sandy fill' (Seto et al., 2009).

2.9.5. Documentation

Record keeping is an indispensable component of construction. Its value is amplified when repairs, modifications, or disputes arise over the structure. The quantity of record keeping necessary will depend on the type of work performed and the amount of supervision provided. Examples of record keeping may include the following (U.S Department of the Interior Bureau of Reclamation., 1998):

- Record of every test performed in the field and laboratory
- Daily or shift reports documenting progress, performance, and factual commentary
- Task specific inspection records noting observations, measurements and modifications
- Weekly or monthly reports summarizing daily activities, schedule and budget progress

Consistency in reporting holds the same importance as for inspections. Developing standardized terms, classifications and descriptors may be necessary to maintain continuity on how documentation is performed. This is amplified on a large-scale project with numerous personnel involved.

2.9.6. Survey

Survey controls serves to provide construction guidance on where materials are to be placed and how thick. Common practice is for surveyors to use Global Positioning systems (GPS) or total station equipment to lay out the locations and limits for placement as well as survey the completed surface for verification and as-built records. GPS systems can now be installed in heavy machinery such as dozers, graders and haul trucks (Gulal & Akpinar, 2003). With this technology, design files can be uploaded to the GPS unit and aid the equipment operator in the transport and placement of fills.

2.10. Instrumentation

Instrumentation is used to monitor and assess the performance of the dam to confirm the anticipated performance is being met. The following parameters are commonly monitored during construction: (1) pore pressures in both fill and foundations, (2) earth pressures, (3) deformations, and (4) seepage flows (U.S Department of the Interior Bureau of Reclamation., 1998). These parameters can provide indicators on the performance of the structure and if remedial measures are necessary. The implementation and monitoring of instrumentation are an integral part of implementing the observational method (Peck, 1969).

2.11. Oil Sands Overburden Dam Construction Methods

Construction methods for a large overburden tailings dam in the oil sands can be similar to conventional practices, however often on a larger and accelerated rate. Table 1 provides a general summary of the differences between conventional and oil sand overburden tailings dam construction methods. Discussion on these construction methods is provided in the following subchapter.

Table 1. Conventional vs. oil sands overburden tailings dam construction methods

Conventional Dam	Oil Sands Overburden Tailings Dam
• Short construction period • Limited by weather and climate • Narrow range of fills with tight construction controls • Optimized dam geometry to reduce fill quantities • Thin lifts (0.3 m) with conventional rollers • Standardized testing protocols • Construction rates based on size of equipment and material sources	• Several years to decades of staged construction • Winter construction methods • Broad range of fill types, no moisture conditioning • Geometry optimized to provide storage for overburden waste within footprint • Thick lifts (1m), compacted with haul truck traffic • Combination of qualitative and quantitative construction controls • Rapid construction rates of 150,000m^3/day and greater (Ashton & Cameron, 1995)

Construction methods relate to the process undertaken to successfully construct the desired structure, in this case a dam. The steps can generally be summarized as follows:

- Site development and preparation for construction;
- Sourcing fill materials which satisfy design criteria and transporting them to the construction site;
- Coordination of equipment to achieve necessary construction tasks;
- Organization of placing and compacting fills within the boundaries and conditions established by design;
- Implementation of quality control measures to confirm that the design goals are being met;
- Optimize the process to perform in an efficient manner to minimize cost and control the construction schedule.

These methods are summarized below, with a focus on the sourcing, movement and placement of fills. Figure 13 provides a flowchart of typical construction sequence. At each of these steps, quality control measures are implemented.

Figure 13. Construction Sequence Flow Chart

2.11.1. Material Sourcing

The optimization of available materials on site for the safe use in a dam is a high priority for both the designer and mine operator (McRoberts, 2008). The goal then becomes to match needs of tailings plan and dam design with available materials from all waste streams. A thorough understanding of the local conditions is necessary, as generous assumptions of the quality and quantity of available fills will impact mine operations further down the road (McRoberts, 2008).

For example, a lease with dense dry fills from Quaternary, Clearwater, and McMurray Formations are well supplied for the use of overburden as dam fills (McRoberts, 2008). Leases with wetter deposits may increase the demand for waste dump storage and more stringent quality controls for fill placement. The optimal combination will not only differ between leases in different geographic locations but also as mining progresses within the open pit, exposing different geological sources.

The use of tailings sand to construct oil sands tailings dam has been commonplace for decades and has been used to build some of the largest earth-fill structures on earth (Morgenstern et al., 1988). However, the focus of this thesis is on the utilization of overburden waste streams.

Engineered properties of soil can be altered or improved by applying the following: (1) the process of selection, (2) controlling moisture content, (3) mixing, (4) stabilizing, or (5) compaction (U.S Department of the Interior Bureau of Reclamation., 1998).

Moisture conditioning and stabilizing methods of soil improvement are typically not feasible during construction of an oil sands dam due to the volume and speed at which fill is moved and placed. In addition, the overburden fills commonly available in the oil sands are water sensitive (Cameron et al., 2001), meaning their geotechnical behavior alters negatively due to the addition of water. Thus, fills must satisfy their design criteria essentially in-situ and be suitable for immediate placement in the dam. Overburden is ultimately strategically mined from the open pit and hauled directly to the dam.

While the majority of fill is controlled simply by strategic selection of in-situ soils, material blending provides an additional method to achieving a desirable fill product from materials that individually may not satisfy the required conditions, such as zones of dry and wet soils. Blending can be achieved directly on the pit wall with full face raking (Ashton & Cameron, 1995) as well as during the process of transportation and placement.

The use of hydraulic and electric shovels used for mine production from the open pit aid in the supply and blending of fill materials for dam construction. The capacity of these buckets may range between 26 to 60 cubic metres, thereby affording significant volumes to be moved per bucket. The shovel bucket will thinly scrap the face over the pit wall over a vertical span of 8 to 15 m, thereby potentially crossing through multiple geological facies and producing a blended fill.

Further blending of material occurs as multiple bucket loads are placed into a haul truck and again at the construction front, as trucks from multiple sources may place fills adjacent to each other. These piles are then mixed together as the dozer spreads the fill into the advancing lift.

Overburden and interburden deposits from Quaternary, Clearwater, and McMurray Formations are potential sources for construction materials (Morgenstern et al., 1988). The amount of overburden suitable for fill placement will depend on the geology and site conditions of a specific lease. The quality and condition of materials can be variable; thus, quality control is necessary within the borrow source. Fills are typically placed at their in-situ moisture content due to the high rate of construction. Furthermore, moisture conditioning of some materials such as till and lean oil sands has been found to negatively impact the soil behavior (Morgenstern et al., 1988).

Quaternary units are the first accessible soils available for sourcing. Construction of an external tailings facility typically starts early the life span of a mine, therefore fills from these units may be used until alternative sources become available as the open pit is developed deeper. Quaternary units consist of mostly glacial deposits such as glaciolacustrine silts and clays, glaciofluvial sand or gravel deposits and tills (Carrigy & Mellon, 1959). Variability in soil types and moisture contents can be anticipated.

Clearwater clay shales are a potential fill material that require quality control measures for use. Clearwater fills are dispersive in contact with water, albeit to a lesser degree in process affected tailings waters (McRoberts, 2008). In addition, in-situ Clearwater deposits commonly contain pre-sheared or slickensided seams with low shear strengths. Thus, for Clearwater materials to be used as a dam fill in any sort of impermeable role, it is imperative that the compacted fill is structure less and free of voids.

Clearwater materials are typically dry, blocky, with a high undrained strength. Conventional compaction equipment was ineffective at competently breaking down the blocky nature to a tight homogeneous state. Fortunately, the advent of using heavy haul trucks with significant compactive energy facilitated the use of Clearwater fills to become a viable material source (McRoberts, 2005).

Strength characteristics of the oil sands were first looked at by (Hardy & Hemstock, 1963) and its four-phase system: sand, bitumen, water, and gas was identified. Further study was performed by (Lord & Cameron, 1985), evaluating the geotechnical properties of lean oil sands. The geotechnical characteristics to be considered were as follows:

- The maximum allowable bitumen content for lean oil sand backfill is generally between 8 and 9%, with the minimum acceptable dry density considered to be 1700 kg/m3
- Oil sands can have highly variable bitumen, fines, and moisture contents between locations, all of which will affect the maximum dry density available
- Increased bitumen content lowers the maximum dry density
- Oil sands are very sensitive to moisture due to bitumen content and will have poor trafficability at optimum moisture contents.
- Lift thickness depends on compactive equipment used, but a maximum loose lift thickness of 1 m was recommended, using up to 170 Ton trucks.

2.11.2. Transportation of Materials

Haul trucks are used to transport ore, solid mine waste and overburden. Advancements in technology has seen the size and capacity of haul trucks increase significantly, with modern equipment capable of transporting over 400 Ton payloads (Koellner et al., 2004). Heavy haulers in a mining fleet may range between 170 Ton and these 400 Ton trucks. For the Syncrude Highway Berm, 170 Ton to 240 Ton haul trucks were used for transporting and compacting fills (Ashton & Cameron, 1995).

Logistical challenges arise when transporting significant volumes of fill daily. A combination of quality control and construction coordination is necessary to satisfy that the transported fills are both suitable for fill placement and is delivered to the appropriate place in the dam. These measures must be performed in an efficient manner, such that equipment does not sit idle or slow down the construction rate.

To assist in the construction coordination of a haul truck fleet, a dispatch system may be used. Incorporating the use of GPS in haul trucks has enabled operators to identify whether a truck is carrying ore or waste materials and direct the truck accordingly (Koellner et al., 2004).

2.11.3. Fill Placement and Compaction

Fill is hauled by truck to the active work front and placed into its designated area, as defined by the material type and its function in the dam. The material is typically spread onto the existing lift then compacted, Figure 14. The thickness of a lift is dependent on the material type, design criteria and the compactive equipment available. (Fell et al., 2005) provides a guide on reasonable lift thicknesses according to their general material types. Where familiarity with the fill type is limited, or variability in geotechnical properties is anticipated, the prescribed lift thickness may be determined by test fills.

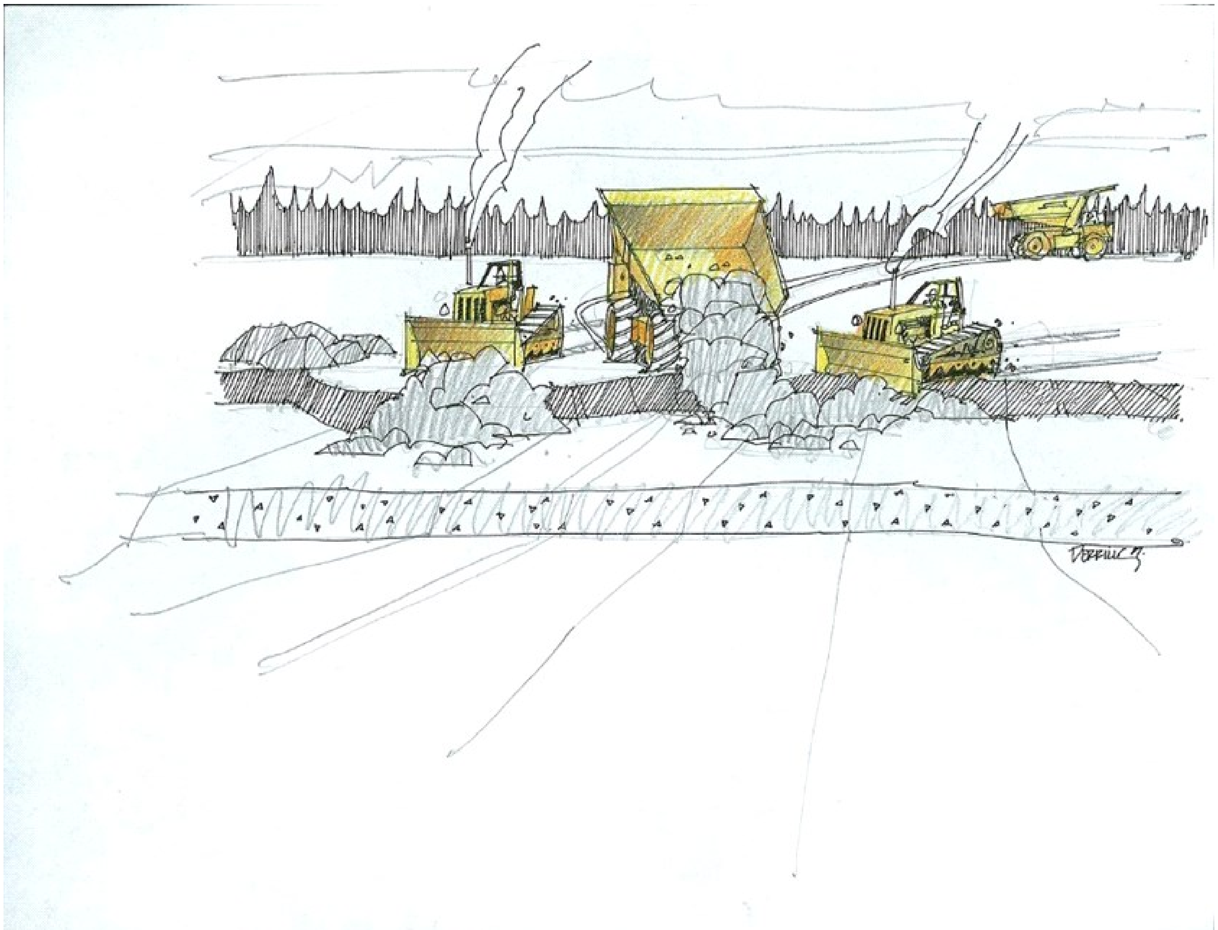

Figure 14. Placing and Spreading Fills (BGC, 2010)

Compaction of fills is performed to minimize settlement, increase the strength characteristics of the soil, and reduce permeability (Das, 2005). This is achieved with the use of compactive equipment performing a prescribed number of passes over a defined area of placed fill. Conventional equipment may consist of various forms of rollers ranging in weight from a few to 50 tons (Fell et al., 2005). The type and size of a roller will vary on the type of material placed and the thickness of the lifts.

Pioneering in the oil sands industry identified the potential to utilize haul trucks as compactive equipment (Cameron et al., 1995). The use of haul trucks for compaction allowed for the thickness of lifts to be increased due the compactive energy applied with haul trucks, thereby allowing a greater volume of fill to be placed at once while achieving the required density ratio. Construction of Syncrude's Berm used 170 T to 240 T heavy haulers for compaction. One set of rear dual tires would measure 700 kPa of pressure over an area of 1 m x 3 m, depending on weight distribution (Ashton & Cameron, 1995). Lifts ranged between 0.75 m thick to 1 m for critical fill zones, and up to 5 m thick in less critical areas, such as toe berms. Compaction was performed with two to four passes performed with a loaded haul truck. Trucks travelled at an approximate speed of 5 km/h and turning was avoided to prevent disturbing the lift.

The compactive energy afforded using haul trucks allow the utilization of material sources that were previously considered unsuitable, such as the dry blocky fills with high dry strength sourced from the Clearwater Formation (McRoberts, 2008).

A consequence of haul truck compaction is the increased risk of rapid pore pressure generation in sensitive fills (McRoberts, 2008). This may lead to concerns in stability, as well as inducing rutting and trafficability issues. Given the low permeable soil type, large volumes and rate of construction, it is unlikely that the dissipation of pore pressures will be achieved for several years. Thus, management of pore pressure generation must be addressed in the design.

2.11.4. Winter Construction Experiences

Winters in the Fort McMurray region are long and cold while the summers are short lived and commonly wet. Restricting construction only to the few available summer months caused ineffective use of the haul truck fleet and posed significant challenges to following construction schedules. However, construction in winter can be problematic as the fill materials will freeze during transport and compaction. Frozen fills will not achieve the same density ratio via compaction as unfrozen fills and thus are prone to softening and differential settlement upon thawing (U.S Department of the Interior Bureau of Reclamation., 1998).

In the late 1970's, Suncor pioneered winter construction methods (McRoberts, 2005) after observing favorable geotechnical behavior in waste dump shells constructed in winter and conducting successful test trials. Other oil sands operators following suit shortly after and winter construction is now common place in industry.

The winter construction trials conducted by Suncor (McRoberts et al., 1983) used haul trucks with exhaust heated dump boxes were used to extend freezing time during transport. Haul trucks with larger capacity can retain in-situ ground temperatures of excavated fill for longer before freezing.

The frozen face of soil at the borrow source was removed and the unfrozen material was mined as dam fill. Haul times were kept short, approximately 30 minutes, to minimize exposure. Loads were dumped and spread quickly to the specified lift thickness and compacted shortly after with a sheep foot packer. Quality controls included the exclusion of snow and ice, along with frozen or wet materials. Close supervision was implemented throughout.

A summary of the observations found from the trials are provided below (McRoberts et al., 1983):

- Temperature variations had an influence on compaction, such that dry density tends to increase with air temperature.
- Average percent compaction of optimum densities taken from the winter trials were found to be within the same tolerable ranges required for summer construction at Suncor.
- Density was observed to increase up to 10 passes for the first 30 cm of a lift, however any additional passes were found to not improve density. This was believed to be due to fill freezing within the observed period of time.
- Lifts thicker than 30 cm were observed to have a decreasing density with depth. A maximum lift thickness of 45 cm was recommended for winter fill to avoid loose or low-density zones.
- Water content was observed to be less during winter construction, likely due to the presence of snow, which can be removed, compared to rainfall.
- Lower water content helped reduce pore pressure ratios during construction, however pore pressures were prone to increases upon thawing if the desired density was not achieved before freezing.

Overall, fill placed in winter conditions were found to perform equivalent to summer conditions, provided sufficient quality controls were implemented and maintained. Fill must be transported, placed, and compacted prior to freezing. Frozen fill in a dam must be anticipated to thaw over the span of the design life and the resulting settlement must be considered. Syncrude’s Highway Berm used similar winter construction methods and stringent quality control measures, with variations due to differing designs and equipment used (Cameron et al., 2001).

2.12. Summary of Embankment Dams Constructed in Oil Sands Mining Environment

The following is a summary of the topics discussed in Chapter 2:

- The geological setting of the Athabasca oil sands is a complex and variable series of deposits generally consisting of Holocene and Pleistocene surficial and glacial deposits overlying Cretaceous Clearwater clay-shales and sand deposits (Carrigy & Mellon, 1959). This is in turn underlain by the ore-producing McMurray Formation oil sands, followed by the Upper Devonian calcareous muds and limestones.
- The oil sands mining process produces significant quantities of tailings which must be stored on site in tailings facilities composed of earth-fills or other materials such as tailings sands (Eshraghian & Becker, 2014). This thesis is on external tailings facilities, specifically those constructed from overburden materials.
- Optimization of available materials on site, especially those from waste streams is paramount for effective operation and environmental acceptability (Morgenstern et al., 1988). Adapting dam design to accommodate these waste streams provides fill sources at low cost while minimizing the demand for waste storage areas. Quality control measures must increase to manage the variable materials encountered. Lack of understanding of the materials properties available has the potential to significantly impact operations later in the mine life (McRoberts, 2008).
- The tailings overburden dam cross section will vary based on design, site conditions, design life span and available fills (McRoberts, 2008). A typical cross section may consist of a low permeable core with adjacent filter zones and upstream and downstream shells. This typical cross section has evolved over time, with design progressing in an iterative process between operational, technical and economic needs (Cameron, 2013).
- The design standards for industry (Eshraghian & Becker, 2014) and application of the observational method (Peck, 1969) were introduced. Common design considerations for oil sands overburden tailings dams include slope and foundation stability, pore pressure generation in fills, and internal erosion.

- Method and performance based specifications may be used in combination to provide construction control (Fell et al., 2005). Quality control measures will mirror the types of specifications used. Quality controls must be fit for function such that the methods used accurately represent the work performed in a manner that can be compared to the design criteria. Standardization and continuity is important between quality control personnel.
- Overburden tailings dam construction methods may differ from conventional methods due to the volume of fills to be moved and size of equipment available. Haul truck compaction provides significantly greater compactive power than conventional rollers and has enabled the use of fills and lift thicknesses previously considered unattainable (McRoberts, 2008). Winter construction methods have enabled year-round construction when sufficient control measures are implemented.

3.0 CNRL Horizon Oil Sands Dyke 10

Horizon Oil Sands is an open pit mining facility developed by Canadian Natural Resources Limited (CNRL), located approximately 80 km north of Fort McMurray, Alberta. In 2012, The facility produced 110,000 barrels of synthetic crude oil daily and is planned to gradually expand to approximately 232,000 barrels per day (Sisson et al., 2012).

An External Tailings Facility (ETF), is required for tailings deposition over the first 10 years of operation, until the open pit has been sufficiently mined to allow for the construction of in-pit dykes. The ETF, a dyke designated as Dyke 10 and shown in Figure 15, is horse-shoe shaped providing impoundment along the north, south, and east perimeters, while the western perimeter is retained by a natural hillside consisting of low permeable in-situ deposits (Sisson et al., 2012). A diversion system was constructed to divert runoff water from the western uplands away from Dyke 10.

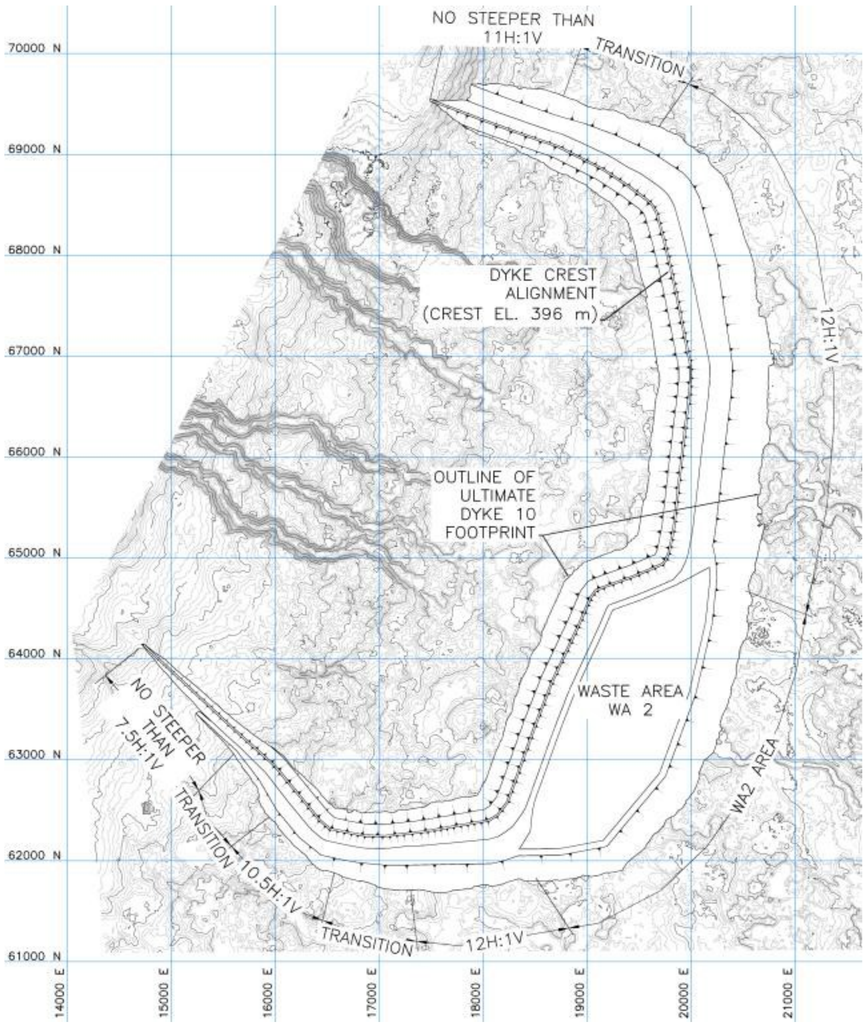

Figure 15. Dyke 10 Alignment (Sisson et al., 2012)

Dyke 10 will have a final typical crest height of 60 m, a crest width of 18 m and a crest length of approximately 13 km. It has been constructed predominantly from overburden and interburden fills stripped from the open pit, with the total volume estimated to be approximately 250 million cubic metres. A thorough description of the geotechnical design for Dyke 10 has been published by (Sisson et al., 2012). Key components of the design are summarized in subchapter 3.3.

3.1. Geology

Foundation conditions within the project limits are discussed in (Sisson et al., 2012) in detail, based on information derived from field investigations. To summarize, the local geology consists of Quaternary soils from 2 to 20 m thick, overlying the Clearwater Formation on the order of 40 to 50 m thick, and the McMurray Formation on the order of 80 m thick. The limestone Devonian Waterways formation underlies the McMurray Formation.

The Quaternary Holocene soils are primarily composed of recent organic deposits and sand or clay deposits. Muskeg within the Dyke 10 footprint was up to 2 m thick with localized pockets of 5 m thick deposits. Natural moisture contents of the alluvial deposits ranged between 10 and 40% with medium to high plasticity clay deposits.

The Pleistocene soils consist of glacial deposits of silts and clays, sands and gravels, and tills. Clayey till is the most prevalent facies at Dyke 10. Natural moisture contents range from 15 to 30% and the plasticity is typically medium to high. Rafted Clearwater and McMurray zones were observed near the bottom of the Pleistocene unit.

The underlying Clearwater Formation is a marine deposit composed of interbedded silty clay to clay shales, with numerous low-density facies and siltstone layers. It is typically medium to high plastic. Shear zones are prevalent throughout. The low-density facies, shear zones, dispersive nature, and thickness of this formation make it a governing factor in the stability design of the structure. The McMurray Formation is generally a very dense and strong deposit with weak clay facies are present at depth (approximately 50 m or greater).

3.2. Mine Waste Management

Waste management pertains to the strategic approach necessary to handle the significant volume of material removed from the open pit. A number of tools and techniques are available to the operator to optimize handling materials, specifically waste.

For CNRL, the primary approach is the incorporation of mine waste into the construction of Dyke 10. The structure serves multiple purposes: retention of process water for recycling, and containment of both hydraulically placed tailings and overburden waste; waste materials are placed in specific methods and in strategic locations based on their geotechnical properties to service the design criteria of a dam (Sisson et al., 2012).

3.2.1. Mine Planning

At CNRL, mine planning logistics are generally broken into three categories: long-term, mid-term, and short-term needs of the mine operations. The long-term planning addresses eighteen months from the current timeframe to the life of mine and closure. Mid-term planning is broken down into two further groups, one focusing on the time frame of four months to eighteen months ahead, while another encompasses the shorter two to three month lookahead. Short term planning operates on the immediate needs, detailing monthly, weekly, and daily plans (J. Obrigewitsch, personal communication, December 15, 2017).

Logistics for Dyke 10 require the involvement of short to long term planning. Day to day logistics of coordinating equipment, materials, and construction personnel are captured with-in the short-term planning, while activities such as tailings deposition and sourcing materials from developing areas of the pit fall under mid-term planning. Long term planning, known as Strategic Planning at CNRL, plays a role in the overall design of the structure, operating and closure conditions. Once the preferred dam footprint has been established, it is handed over to the geotechnical group, to manage the construction and performance monitoring.

At CNRL, the members of the planning groups are integrated and meet at least once a week, along with collaboration between the geological and geotechnical engineering groups. While each group has its own responsibilities, for efficient operations it is important for these groups to function cooperatively and be well informed.

The staff are located in the same office and work within proximity to each other. This proximity is a catalyst for effective communication and facilitates the optimization of planning for each group individually and collectively. Resources such as the block model and the dispatch system are used to coordinate the movement of ore and waste materials are accessible by all parties (W. Abeda, personal communication, September 30, 2015). This serves to facilitate communication and prioritize tasks appropriately.

3.2.1.1. Block Model

The block model is a tool for mineral resource estimation (Darling, 2011) and is valuable component of mine planning. The orebody and surrounding geological units are broken into discrete blocks, with each block containing its own unique set of material properties (Lamghari et al., 2014).

The material properties are assigned according to the geological interpretations from investigative drilling and geological studies. Blocks are then categorized as being profitable or as waste, based on the overall mine plan and its criteria for ore grade. Waste blocks are commonly necessary to excavate to access the underlying profitable ore blocks (Lamghari et al., 2014). The logistics of the excavation sequencing is a driving component of the mine plan.

At CNRL, the material properties in the block model includes geological classifications, bitumen grades, and fines content (W. Abeda, personal communication, September 30, 2015). The bitumen grade indicates whether the material in question is viable for ore production. The fines content aids in determining the geotechnical classification of material type. The coordination of mining activities can then be optimized by identifying target areas such as high bitumen grade for ore production, or specific soil types for use as fills in construction.

The CNRL geological block model relies on data collected from boreholes performed with 100 m spacing between locations. An individual block from the model represents the geological properties of a 3 m x 25 m x 25 m zone, based on the feasibility of mining a block economically.

More specific to waste management, this geotechnical data allows the evaluation of the waste material being hauled, in terms of its suitability to perform as fill. This tool has the potential to further optimize the utilization of waste materials by adding an additional degree of predictability to the expected material types, thereby allowing the operator to coordinate mining activities effectively.

The optimal time for the incorporation of geotechnical data into a block model is essentially as early into the operation as possible. This allows an additional source of information mine planners can use to minimize high wastage, typical at the startup of construction. While still valuable further into the mine life, at later stages it is probable that empirical correlations and familiarity with site conditions diminish the cost effectiveness of incorporating geotechnical data into the block model.

3.2.1.2. Capture Rates

The capture rate can be considered as a quantifiable measure of the amount of material utilization achieved, or in other words, the percentage of material excavated from the pit that is either taken for ore production or repurposed as fill. The remaining excavated material is material that must be stored in waste dumps.

The ideal capture rate is as close to 100% as possible, as this indicates the excavated material has been utilized in some way or another, thereby reducing the demand for storage space and equipment to manage this waste. In reality, the capture rate is a constantly changing function of complex site geology, mining methods, and the robustness of design to accommodate a broad range of fills.

At CNRL, the capture rate has improved significantly since the commencement of construction, progressing from 40% to a planned capture rate of 80% during peak construction, which often performed up to 90% efficiency (W. Abeda, personal communication, September 30, 2015). This improvement can be attributed to the following factors:

- Availability of multiple soil types in pit
- Robust design capable of accommodating variable soil types
- Enhanced understanding of geological conditions through experience

There is a limited availability of fill options during the initial stages of the open pit, governed by the site geology and rate of excavation. Till was the primary borrow material for the core zone of the dam but was prone to high wastage due to the prevalence of wet and soft conditions. Further excavation of the open pit exposed alternative fill options for the core, such as the Lower McMurray Formation, which have provided a more continuous and consistent borrow source for the core.

Robustness in design allowed for modifications to the design and fill specifications based on the soil types encountered. Modified construction techniques, such as slop cell construction, have been utilized to incorporate soft and wet materials that would have other been wasted. The modifications are further discussed in Chapter 3.5.

As expected with the development of any new site, there is a learning curve to understand the site geology and developing efficient mining and construction practices specific to site conditions. As the site matures, the knowledge and experience acquired through trial and error can be used to optimize mining and construction practices to minimize this. Efforts to shorten this learning period have obvious financial and schedule driven benefits. Improved accessibility to data used for mine planning and construction, such as incorporating geotechnical data into the block model, is an example of an opportunity to minimize the degree of trial and error required.

3.3. Geotechnical Design

3.3.1. Design Criteria

The purpose of the Dyke 10 external tailings facility is to provide tailings storage for the initial years of operating, approximately 10 years in length, and provide recycle water storage for the life of mine (Sisson et al., 2012). The dyke was designed to satisfy the dam safety guidelines as set by the Canadian Dam Association (CDA., 2013), and follow the best practices established in the oil sands industry. The observational method (Peck, 1969) was employed to optimize the design in terms of risk management.

The Horizon lease has a high overburden to ore stripping ratio, resulting in a significant volume of overburden material to be moved. Thus, the dam was designed to be constructed entirely out of overburden and interburden accumulated from mine waste. Flexibility in the design for broad fill specifications to allow for a greater range of mined out materials to be utilized was paramount.

The observational method was an essential component of the design for Dyke 10. “Most likely” and “reasonable worst” cases were established for the stability analysis. Design and construction commenced under the most likely case, with mitigation measures developed to respond to less desirable performance observations (Sisson et al., 2012).

3.3.2. Key Design Issues

Low mobilized shear strengths in the clay shales of the Clearwater Formation and internal seepage controls for the core materials are the two main design issues for Dyke 10 (Sisson et al., 2012). Seepage control measures were necessary to mitigate the risk of internal erosion and the potential for a piping failure (Sisson et al., 2012). Control measures necessary for Dyke 10 included the following:

- Dispersive soils such as those present in the Clearwater Formation must be restricted from critical zones of fill in the dam, specifically the core.
- Internal drain systems must provide sufficient drainage capacity to prevent the build-up of pore pressures
- Filter materials must be cohesion less and appropriately graded to be sufficiently permeable while grain-size compatible to resist piping
- The potential for cracking of fills in critical zones due to mechanisms such as differential settlement must be mitigated

3.3.3. Typical Dyke Cross Section

Dyke 10 is a zoned dam consisting of core, filter, and shell zones. It is constructed via the downstream construction method. The foundation elevation varies with approximately 20 m of relief, resulting in a maximum localized crest height up to 71 m. Figure 16 provides a typical cross section through the dam.

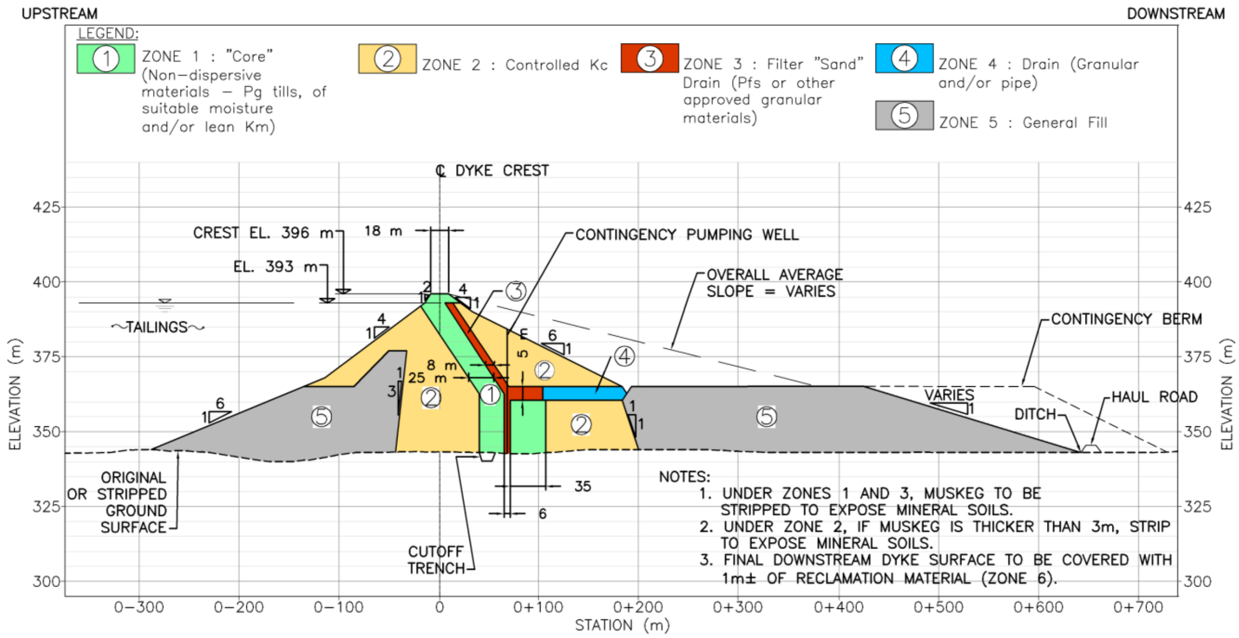

Figure 16. Dyke 10 cross section (From Sisson et al., 2012)

The fills used consist of overburden and interburden fills stripped from the open pit, with the total volume estimated to be approximately 250 million cubic metres. Dam fills were broken down into zones designed to suit the range of materials expected to be encountered from the mine stripping, while satisfying design criteria.

Zone 1 functions as the low permeable core, which is structurally supported by Zone 2. Both zones have relatively strict specifications and quality control measures to satisfy that design criteria are met. Zone 1 also provides a buffer between Zone 2 and the dyke filter material, Zone 3, which comprises the chimney drain and drainage blanket. As the Clearwater Formation fills can be dispersive, the buffer of Zone 1 is necessary to protect the filter from contamination. Zone 5 provides support and weight over the footprint of the structure for stability, while partially functioning as a waste dump for pit materials that do not satisfy the specifications for Zone 1 and Zone 2. The zones of the dam are summarized in the following table (Sisson et al., 2012) and (CNRL, 2011).

Table 2. Summary of Fills (CNRL, 2011)

Zone	Material	Description	Fill Source
1	Core	• Primary low permeability seepage barrier. • Non-dispersive soils.	• Multiple material types which satisfy specification criteria, including: Tills, lean oil sands, McMurray Formation Interburden
2	Controlled "Kc"[1]	• Structural support for core. • Dispersive soils allowed under tight quality controls. • Must be compacted to a tight homogeneous state	• Clearwater Formation fills: • Zone 1 fill may be used.
3	Filter Sand	• Cohesion less filter designed to control seepage and primary defense against piping.	• Nearby fluvial deposit. • Filter is compatible with Zone 1 filter criteria
5	General Fill	• Broadly specified fill to allow for wide range of material types and quality. • Functions as a waste dump • Stability berm where needed. • Slop cell or layered fill construction is allowed for wet fills	• Available overburden waste which satisfy fill specification

Note:
1: Kc is the geological abbreviation for fills from the Clearwater Formation

The downstream slope predominantly ranges from 7.5H:1V to 12H:1V. Where the downstream slope is incorporated with a waste dump and foundation conditions required it, the overall slope is shallowed to 20H:1V to 25H:1V. The upstream slope ranges between 6H:1V to 2H:1V, according to elevation. The steepened slopes are based on volume optimizations in the stability analysis and relying on pond contents for buttressing at higher elevations.

Given the dam geometry, the downstream slopes can be exceptionally long. A filter blanket along the base of the dam would require significant quantities of sand fill, at considerable cost

(Sisson et al., 2012). Thus, Dyke 10 utilizes an inclined core and chimney drain to significantly reduce the required volume of critical fills while providing sufficient overburden stress to reduce the risk of hydraulic fracturing in the core.

The chimney drain and horizontal drainage blanket configuration is a unique design with significant cost benefits. By elevating the horizontal drainage blanket and outlet, the volume of filter sand required was significantly reduced (Sisson et al., 2012). Further seepage control measures include a collector drain at the end of horizontal blanket which runs along the length of dyke, outlet finger drains constructed of Zone 3 sand spaced every 200 m, a seepage cutoff trench, and a seepage collection ditch along the dam perimeter.

The risk of piping is mitigated by redundancies in the design such as: (1) low permeability fills upstream of filter, (2) large overburden weight to resist hydraulic fracturing, (3) crack plugging enabled by internal segregation, (4) filter cake development, and (5) drainage in foundation sand channels (Sisson et al., 2012). The observational method was implemented, and a mitigation plan was developed to further manage the risk of piping. The plan consists of the option of installing and operating a series of pumping wells to lower the phreatic surface within the chimney drain if necessary.

3.4. Specifications

Long term tailings dam construction within an operating mine provides a unique opportunity in the development of specifications. Short term, tendered, construction projects may be constrained by a limited scope, where specifications must be well defined. Changes to the specifications in this scenario can be cumbersome and have significant financial implications. This may be at odds with operating conditions of the mine, where varying market prices and variable site conditions may motivate an operator to expedite or postpone construction activities. However, a well-equipped mine is capable of internally sourcing construction crews and equipment. This provides flexibility for the operator to function within the long-term goals of the mine and respond to short term needs. In turn, the specifications for such long-term construction can be more broadly defined.

Dyke 10 was contracted in such a manner that scheduled a gradual phase out of a contractor as CNRL's own forces took over construction planning and activities. For the first three years, the contractor provided 100% of the construction planning, equipment and personnel for the project. Over the subsequent three years, the construction planning roles were reduced to 50%, while CNRL personnel transitioned into these positions. After six years, the contractor's role was further reduced and was no longer involved in planning but maintained responsibility for approximately 50% of the project plant. As part of this transition, CNRL purchased equipment from the contractor.

Specifications for Dyke 10 were developed to satisfy the design requirements and utilize material on site in a manner that satisfied geotechnical design criteria. For the construction of Dyke 10, a combination of performance and method based specifications were implemented. This combined system permitted acceptance based on objective testing and performance of placed fills, balanced with subjective construction methods (CNRL, 2006).

Performance based specifications require routine quantitative quality control tests to be performed and evaluated against minimum design specified criteria. However, given the volume and variability of fills transported and installed at Dyke 10, a solely performance specifications would be highly complex and difficult to implement. The frequency of testing that would theoretically be required becomes impractical. Thus, method specifications are utilized in combination to provide construction control.

The method based controls used at Dyke 10 and the way in which the managing personnel have implemented them are built upon the precedents set by Cameron, McRoberts, and others in the oil sands. Operators are now capable of greater rates of production with larger equipment and modern technology. CNRL's quality control and quality assurance methods have had to adapt in order to manage the rapid rate of construction, with a greater emphasis applied to the daily observations by quality control personnel monitoring construction. The challenge then becomes standardizing these observations via a controlled system that is consistent, repeatable, and can hold up against scrutiny. This is further discussed in Chapter 3.6.

3.4.1. Test Fills

The development of method specifications requires empirical exercises, such as test fills, to establish construction parameters. Initial assumptions of the compaction parameters to be trialed are developed based on industry experience and published literature on similar construction projects in the oil sands. These parameters were then modified to suit site specific conditions and materials, based on the observations derived from test fill trials. The compaction parameters typically evaluated in the test fill include the following:

- Lift thickness
- Type and weight of compactive equipment (i.e. haul truck)
- Number of passes and overlap
- Rut and roll or similar deflection criteria for evaluation

Test fills were performed on the individual proposed material types intended for fill placement within the dam, beginning with Till and continuing with Clearwater and McMurray Formation soils as they were encountered. As alternative fill sources are exposed in the open pit, further test fills are performed to evaluate the suitability of the potential fill source for fill placement.

A key focus of test fills performed at Dyke 10 was evaluating the ability for a haul truck to successfully breakdown dry, blocky particles ‘lumps’ of fill via compaction to form a homogenous, structureless mass. The general procedure to perform such a test fill is summarized below, based on a test fill performed to assess the suitability of interburden material for use in Zone 1 (AMEC, 2009).

The fill to be evaluated was spread by dozers and compacted by haul trucks in a low risk area of the dam, while lift thicknesses of 0.75 m to 3 m thick were trialed. A test trench was subsequently dug through the test fill area to expose a cross section of the test fill for visual inspection, as shown in Figure 17.

Figure 17. Trench excavated for a test fill. (CNRL, 2018)

The inspection of the trench side walls indicated that not all the lumps, which are near a claystone or mudstone state, were broken down to a structureless mass. However, it was found that by limiting the amount of clay lumps accepted in a lift to 20%, the lift would successfully achieve compaction with the lumps fully embedded in a matrix of fine grained soil. Greater than 20% concentration of lumps would increase the potential for point to contact between lumps, which in turn increases the risk for dispersive piping and reduced compaction.

The lift thickness was recommended to be kept at a minimum, as this supported the ability for construction monitors to visually assess the concentration of lumps. Proactive efforts could be taken at the headwall to identify and avoid areas of concentrated lumps for placement.

The procedure summarized above provides an example of the application of a test fill to establish construction methodology to achieve a desired fill performance. The effectiveness of this approach is limited to the implementation of appropriate quality control measures. A general guideline was developed for typical lift thickness as a function of fill and equipment type, based on the results of the test fill investigations, and is summarized in Table 3.

Table 3. Lift Thickness General Guidelines (CNRL, 2011)

Loose Lift thickness (mm)		Compactive Equipment
Clearwater Fills	*Non-Clearwater Fill*	
Less than 300	500	100 Ton to 200 Ton loaded haul truck
300	500 to 750	240 Ton loaded haul truck
750	1000	300 Ton to 400 Ton loaded haul truck

Test fills were performed to develop winter fill placement criteria but are not publicly available. The parameters of interest were the implications freezing had on conventional construction parameters, such as lift thickness, type of equipment required, and exposure time limits. The test trials found that a minimum 240 Ton truck was needed to prevent the freezing of fills while in transport.

3.5. Construction

Both short-term and long-term planning teams are utilized to determine the necessary areas to mine to achieve production goals for both ore and dam construction. The fill used for the dyke is made available by pit release and is therefore a function of productivity in the open pit.

Placement rates can be highly variable depending on pit activities, shovel locations and material types. During the initial years of construction where high waste was observed due to the presence of tills and Pleistocene soils, placement rates could be as low as 50,000m^3 to 150,000 m^3. At peak construction of Dyke 10, the majority of materials were diverted to Dyke 10, and placement rates could reach 250,000 m^3 to 350,000m^3 per day (J. Obrigewitsch, personal communication, December 15, 2017).

In more recent years Dyke 10 is nearing completion. Fill placement has become more technical and requires more control of materials, while capacity of Zone 5 as a waste dump has diminished. As a result, placements for Dyke 10 run closer to 30,000 m^3 to 40,000 m^3 per day, with high placement rates now taking place at new waste dump locations away from the dyke footprint.

A dispatch system is utilized to coordinate and control the transport waste material, using predominately 400-Ton trucks, from the pit to the dyke. At Dyke 10, the dispatch is operated by a team of trained personnel who understand the design intent and geotechnical behaviors of the materials being transported, thereby minimizing the potential for non-conforming fills to be placed within the fill zones.

The dispatch system functions with the use of GPS, which is equipped in each haul truck. Combined with the geological information provided by the block model, the dispatch system can identify the material type in each haul truck and provide the trucks location. The accessibility of the system allows personnel from differing teams, such as quality control or short-term planning groups, to have access to the same information, simultaneously.

GPS in haul trucks is used as quality control tool to verify that the path of haul truck traffic, and therefore compaction, is parallel to the dyke axis, which is a requirement of the specification. Furthermore, haul truck GPS and has been utilized in a forensic manner to retroactively locate errant loads of fill placed in the wrong location or locate fills that did not meet specifications (W. Abeda, personal communication, September 30, 2015).

The dyke is divided into multiple sectors to aid in equipment coordination and geo-referencing locations to facilitate communication. Fill placement typically would not be completed continuously across the dam alignment, but instead stagger between sectors based on operational needs, such as working around tailings deposition.

As a loaded haul truck arrives at the instructed sector where an advancing lift is taking place, the truck dumps their load at the lift face, which is then pushed over by dozer, onto the underlying existing compacted lift. The rate of placement and variability of fills restricts the option of moisture conditioning; thus, fill is placed at its in-situ moisture content. The dozer advances the lift with material continuously being delivered by haul trucks, simultaneously mixing the placed material and maintaining a specified lift thickness (Figure 18).

Compaction is achieved with the use of the same haul trucks which transport the fill material. Truck operators are trained to spread their traffic across the entire lift and stagger their tire pattern to give complete coverage of compaction. Quality control personnel will monitor the construction of a lift, making note of haul traffic direction and evaluating that sufficient heavy vehicle traffic has passed to achieve compaction across the entire lift. Typically, a lift will undergo hundreds of passes by haul trucks using the lift as a haul road, easily achieving the necessary degree of compaction.

Table 4 below, summarizes the construction methodology and performance criteria required for each fill type, as per CNRL's QA/QC plan (CNRL, 2006).

Table 4. Construction Method and Performance Criteria by Zone (CNRL, 2006)

Fill Type	Construction Method	Fill Performance
Zone 1 (Core)	• Max. 1000 mm lift thickness • End-dumped by truck and dozer spread • Compaction via loaded haul trucks sequenced to provide full lift coverage and maximize compaction • Surface of placed fills to be scarified between lifts • Frozen fills not permitted. Compaction to be achieved prior to freezing, typically within 1hr of placement below -10°C	• Trafficable platform • Rut and roll evaluation of localized over wet fills • Material to be placed in homogeneous lifts without large lumps or voids • Fills not to be excessively dry or contain excessive defects
Zone 2 (Controlled "Kc"[1])	• Same as above except: • Max. 750 mm lift thickness and reduced as necessary based on material properties • Transport and compaction via loaded 300T haul trucks or larger	• Same as above
Zone 3 (Filter Sand)	• Max 500 mm lift thickness • Fills not to be over compacted, organize truck traffic to minimize activity over fills • End-dumped by truck and dozer spread • Surface of placed materials not to be overwatered • Limit placement to maximum 3 m during winter • Frozen fills not permitted. Compaction to be achieved prior to freezing, typically within 1hr of placement below -10°C	• Surface traffic to be kept at minimum to prevent over-compaction and contamination • Material to be placed in homogeneous lifts without large lumps or voids

Zone 5 (General Fill)	• Material end dumped in 3-4 m lifts • Smooth the tops of dumped lifts to provided trafficable surface • Place approx. 1 m thick layer of Clearwater sourced material to cap underlying end-dumped fills	• Trafficable platform

Note:
1: Kc is the geological abbreviation for fills from the Clearwater Formation

Areas of the dyke such as contacts between fill zones and ends of activity sectors may not see as much traffic during fill placement. Changes in material types delivered from the pit may also require additional compaction than typically required. These locations may be a focus of quality control personnel to satisfy that sufficient compaction is achieved. An individual haul truck may be pulled out of the rotation to perform additional compaction as necessary.

Following fill placement, the lift, which may span several hundred metres, is evaluated by quality control and approved for subsequent lifts to be placed. Prior to a subsequent lift being placed, a grader will pass over the surface to remove cracked or otherwise defective surficial material from the lift. Depending on the zone of fill placement, clean-up specifications dictate the degree of surface preparation necessary prior to a subsequent lift (CNRL, 2011). Clean-up criteria is generally catered towards the deleterious impacts of inclement weather, specifically rain and winter conditions, further discussed in Chapter 3.5.1.

Figure 18. Fill placement while dozer spreads fill (CNRL, 2015)

The general construction sequence is represented in the following figure. The quality control component of the cycle is involved in every aspect of the construction sequence and influences the construction methodology. This is further explored in Chapter 3.6.

Figure 19. Construction Sequence

3.5.1. Special Conditions: Seasonal Conditions

Significant challenges arise during fill placement in winter months (McRoberts, 2008). However, it has been successfully performed at several operator sites prior to CNRL, as discussed in Chapter 2.11.4. Test trials were performed to develop winter fill placement procedures specific to the CNRL site conditions, as described in Chapter 3.4.1.

Once placed in winter conditions, fills must be compacted prior to freezing. Understanding the time restraints is important; if fill is frozen before achieving compaction and the resulting density tests fail, the fill must be removed at a considerable cost and difficulty. Consequently, fill placement is avoided below -30 °C to minimize this risk (CNRL, 2011).

The project specifications provide fill clean-up criteria to satisfy that undesirable materials are removed from the surface of a lift prior to a subsequent lift being placed (CNRL, 2011). The focus of this clean-up criteria is based around the removal of snow, ice and uncompacted frozen materials.

Generally, clean-up of approximately 90% of the surface area being evaluated is expected for Zone 1 and Zone 2 fills, and 70% for Zone 5 fills, provided the defects left in place are discontinuous and comprise an individual area less than 25 m^2. Defects are items such as ice and snow layers greater than 2mm in thickness, or pockets of soft and wet material, ‘slop’, in pockets up to 75 mm deep, and surficial cracking larger than 50 mm wide by 150 mm deep (CNRL, 2011). These tolerances function to provide a pragmatic approach to satisfying the desired compaction criteria while not being prohibitively difficult to implement.

In the spring time, fills that have undergone the effects of freeze-thaw cycles are scarified, reworked, and recompacted as necessary. Ice enriched fills are removed. Through the warmer seasons, ponded water must be removed prior to fill placement while rain-soaked fills are removed from Zone 1 and Zone 2 areas and placed in Zone 5 or other waste areas (CNRL, 2011).

3.5.2. Special Conditions: Chimney Drain

The chimney drain is constructed by excavating a trench through compacted Zone 2 fill which is placed across the design limits of the chimney drain, see Figure 20. The sand material is then placed up to 1000 mm thick and track packed a dozer (CNRL, 2011). The chimney drain is the only fill type where moisture conditioning is permitted as necessary to achieve the desired compaction. Care is taken to prevent contamination, degradation, or over-compaction of the chimney drain fill, which may reduce the performance of the filter. Haul traffic is kept off the chimney drain unless the appropriate protective measures are in place.

Figure 20. Chimney Drain Construction

The chimney drain is prone to freezing quickly in the winter due to its coarse-grained nature. As the chimney drain serves a critical role in filter criteria, which may be compromised by freezing, thermistors are placed in the filter sand to monitor the temperature of the fill. A maximum of three lifts of the chimney drain are placed over the span of any single year, then capped with Zone 2 fill to minimize exposure while adjacent zones of fill are raised (CNRL, 2011).

3.5.3. Special Conditions: Zone 5 Slop Cell and Layered Construction

Two methods, slop cell and layered construction, have been developed to incorporate the use of wet, soft materials within the footprint of the dam. The locations are limited to designated areas of Zone 5 as determined by the designers. Eventually the capacity for storage of the soft wet materials will be filled, requiring the material to be stockpiled in waste dumps. In the meantime, these two construction methods and the robust design have permitted storage of low quality materials over several years of dyke construction.

Slop cell construction is used to place material that is not capable of supporting construction equipment and is easily mobilize when end-dumped, also known as 'slop' (CNRL, 2011). The method used to construct a containment cell out of competent 'dry' fill, then place the wet, soft material up to 3 m thick within the footprint of the cell, relying on the competent fills of the cell to provide containment. The 'dry' fill is typically material that would be otherwise used for Zone 1 and Zone 2 fill placement. A dozer then pads out over the soft material with additional competent fill up to 2 m thick. This confines the soft material while allowing for blending of the two material types. As the primary function of Zone 5 is to provide weight as a buttress, the settlement incurred by this method is tolerable.

When the wet, soft material can maintain a slope angle of 18°, a layered construction method is sometimes used within designated areas of Zone 5 (CNRL, 2011). Alternating layers of 'wet' and 'dry' materials are placed in approximately equal volumes. Wet materials are end-dumped by haul truck, while the dry material is padded out using a dozer. The wet layer is shaped to shed water and any remaining ponding water is removed prior to a lift of dry material. This is done to prevent further degradation of the wet material to more of a 'slop' consistency.

3.6. Quality Control / Quality Assurance

A driving component of effective quality control is establishing a system that accurately evaluates the necessary parameters that are representative of the design intent. In other words, quality control must be fit for function. The strength of a quality control system comes from the collective commitment and enforcement to the system by the project members, such as the construction personnel, quality control team, and project management. For collaboration to be successful, the goals and criteria from the specifications must be communicated in ways that are easily understood by all the invested parties.

The major challenge facing quality control for a project of this magnitude in the oil sands is managing the variability and volume of fills that must satisfy dam design criteria. Simultaneously, short and long-term production goals must be met in order. Quality control then becomes a function of identifying, tracking, and allocating waste materials based on its behavior and developing methods to optimize the use of material (N. Morgenstern, personal communication, May 15, 2017).

The identification and tracking of waste is in part achieved within the scope of mine waste management (Chapter 3.2), captured within the block model based on site investigations and controlled with real time inspections. The allocation of waste based on its behaviour is incorporated into the robust design of the dyke (Chapter 3.3).

The volume of fills, and resulting rate of placement, requires rapid and responsive quality control methods of critically evaluating fill materials to satisfy that the specifications are being met. The variability of the fills increases the difficulty of evaluating the fill materials in a reliable and representative manner. These two conditions result in the need for unique approaches to quality control methods.

The predominant approach used at Dyke 10 was the reliance on detailed and well documented inspections by qualified personnel. The observations were then corroborated by testing of the placed materials. In this sense, quality control consists primarily of observations of construction methodology and fill performance. Quality control is then calibrated with periodic compaction density testing and index testing to assess compliance with the specifications and verify that the qualitative control criteria remain applicable as conditions change. The following chapter explores the quality control methods used for the construction of Dyke 10, building on the achievements of similar projects in the oil sands.

3.6.1. Management of Quality Control

To develop an effective quality control system, CNRL initially utilized the geotechnical engineering consulting firm responsible for the design and development of the drawings and specifications for Dyke 10. Over the first year of construction, the consulting firm provided quality control and quality assurance services over the construction of Dyke 10, developing and implementing a quality control and assurance system. While the quality control system was not made publicly available for this thesis, key concepts were made available through interviews with CNRL personnel.

Simultaneously, CNRL personnel were trained on the system with the intent of eventually taking over the quality control and assurance roles. Following the initial year of construction, the consulting firm was slowly phased out from the quality control and assurance role and replaced by CNRL personnel.

3.6.2. Inspections and Documentation

The importance of field inspections performed by qualified and experienced quality control personnel, is amplified when managing the large volumes and variability of fills handled at Dyke 10. The execution and analysis of testing data alone cannot keep up with the rate of fill placement without impacting production targets. Instead, the real-time evaluation of materials by equipment operators and on-site inspectors are critical in evaluating field conditions, identifying problem materials, and rectifying issues immediately. This feat requires diligent monitoring and equally diligent documentation which can be readily accessed and understood.

Inspections are carried out at the headwall within the open pit, where material for the dyke is excavated. At the headwall, inspectors evaluate the material type and quality being excavated, compare it to the expected materials as per the block model and evaluate its suitability for fill placement. Samples are taken to support the inspector's interpretation and provide documentation.

On the dyke itself, inspections are performed at the locations of placement and compaction of fills. Here, inspectors again evaluate that the correct material types are being placed and identify problem areas. Placement methods are observed to satisfy that the correct lift thickness is achieved, oversized particles are separated, and that sufficient compaction has been achieved. Parameters such as bitumen content, moisture content, and fines content are visually assessed, sampled and tested to verify.

At the start of the project, while the quality control personnel, or construction monitors, performing inspections had decades of experience, the documentation struggled to reliably communicate that the work completed was compliant with the specifications. The solution was to simplify the specifications into the individual criteria that must be met, such as compaction being performed parallel to the dyke reference line. Construction monitors were to perform inspections and verify that haul traffic, and thereby compaction, was travelling parallel to the dyke reference line.

Inspection reports were revised and required detailed descriptions of the activities observed. The reports required the date and 'to-the-minute' time of inspection along with geo-referenced locations. Standardized terms were used to describe material types, quantities, sizes, and observations that may vary between personnel. Sketches of activities were mandatory, indicating features such as the direction of vehicle traffic relative to reference line and noting whether the activity and materials placed met specification. Relevant communications between the construction monitors and the contractor were documented to provide a permanent record and continuity between shifts (J. Obrigewitsch, personal communication, December 15, 2017).

An emphasis was put on the inspection reports being detailed, clear and coherent. The lack of clarity was found to often indicate disorder and identify a possible issue that required follow up by the quality control team. This approach to clarity was applied to daily, weekly and quarterly reports, which utilized a consistent format to reduce complexity in reporting.

An additional level of resiliency was applied to the reliance on inspections by incorporating tools such as a 'Witness Inspection Point'. A Witness Inspection Point is an unscheduled inspection, similar to an impromptu safety inspection, in which a project engineer or manager performed an on-site inspection of construction activities (CNRL, 2012). The inspections create an opportunity to provide on-site training to the construction monitors to maintain consistency between monitors, while keeping the engineers and managers in touch with the day to day activities and potential arising issues.

At a higher level from the day to day quality control measures, monthly reports are compiled summarizing construction production and quality control records and submitted to the design team for review and scrutiny. Semiannual reports and meetings to discuss the quality control and quality assurance efforts are arranged with the Mine Geotechnical Review Board, which is comprised of experienced industry experts employed to provide an independent technical oversight on items solicited by the operator.

3.6.2.1. Field Issue Resolution

Occasionally quality control issues will arise, such as the wrong material or bitumen rich material placed in a fill zone, or under compacted fills. Incorrectly placed or low-quality fills can require multiple lost shifts of production due to the effort necessary to locate the material through forensic quality control efforts, then excavate through potentially multiple lifts, remediate, and rebuild the deficient area. Depending on the location, this can also delay construction of additional lifts and raises of adjacent zones of fill. At Dyke 10, the cost of remedial or removal of failed material can be approximately five times the cost of regular production (J. Obrigewitsch, personal communication, December 15, 2017).

Construction monitors were trained to escalate issues through the quality control hierarchy, such that the project engineer will be notified, who may in turn defer to their respective manager or design team, depending on the nature of the issue (J. Obrigewitsch, personal communication, December 15, 2017). This hierarchal approach to addressing technical issues provides the opportunity for the best qualified person to handle the issue at hand.

Field issues are typically evaluated on a case by case basis. Solutions can consist of removing material that does not meet the performance or method specifications (non-compliance), remediating the non-compliant fill in place. On specific occasions, a non-compliant issue may be accepted without further treatment, however this acceptance may be based on a risk assessment performed by the owner and the design engineer.

As part of the documentation process, a 'Field Issue and Resolution Form' was developed to supplement inspections. This form functioned as a formal record of a field issue, such as a failed lift that has not yet been remediated, that must be resolved before work in that area can be approved (CNRL, 2012). The document required the involvement and signatures of the contractor foreman and supervisors along with the quality control team and would stay open until a resolution had been achieved.

3.6.3. Education and Incorporation of Construction Personnel

Equipment operators and similar construction personnel, along with their supervisors, can be the most valuable component of quality control. Therefore, educating all staff becomes critical to provide sufficient control over construction methods. It is important to develop relationships between quality control and construction teams to understand that quality control is not a deterrent which limits production, but an asset that enhances the project quality and production, minimizing the need for remedial work. The incentive behind this is straightforward; mistakes are costly and time consuming.

Training or orientation sessions were held for all construction personnel involved in the project and were hosted by the design and project management team. Design concepts and goals were presented in layman's terms. The construction management system was displayed such that staff knew the boundaries of each role and knew when to escalate a problem. Accountability is spread throughout the project team, such that a construction supervisor is equally responsible as quality control personnel to satisfy that activities are performed as per specification (J. Obrigewitsch, personal communication, September 30, 2015).

A handbook or 'cheat sheet' simplifying the construction specifications into key criteria were provided to all field personnel, operators, supervisors, along with the quality control teams. The intent of the handbook was to be carried in the equipment and with the personnel in the field and serve a quick reference guide. Topics within the handbook can be discussed as part of daily toolbox meetings.

3.6.4. Field Testing

Field testing is a necessary part of quality control by providing a quantifiable record of the geotechnical properties of the fills placed within the dyke. The challenge then, is how to satisfy that the sufficient type and frequency has been achieved to be truly representative of the placed fills. It's arguable that they're not, particularly when managing large volumes and variability in fills. However, combining the information acquired through field testing with observational and qualitive data provides a more complete understanding of the materials placed and their performance.

3.6.4.1. Test pits

The goal of compaction is to apply enough compactive energy to achieve a sufficiently dense structure-less unit across the entirety of a lift. The evaluation of this goal is most reliably assessed at Dyke 10 with the use of test pits. Following several hundreds of metres of lift construction, test pits are dug through the completed lift. The test pits are used to visually assess the compacted lift for completeness of compaction and evaluate that the original blocky soil structure has been broken down. Alternatively, the trench excavation performed for construction of the chimney drain can perform as a large-scale test pit, Figure 21.

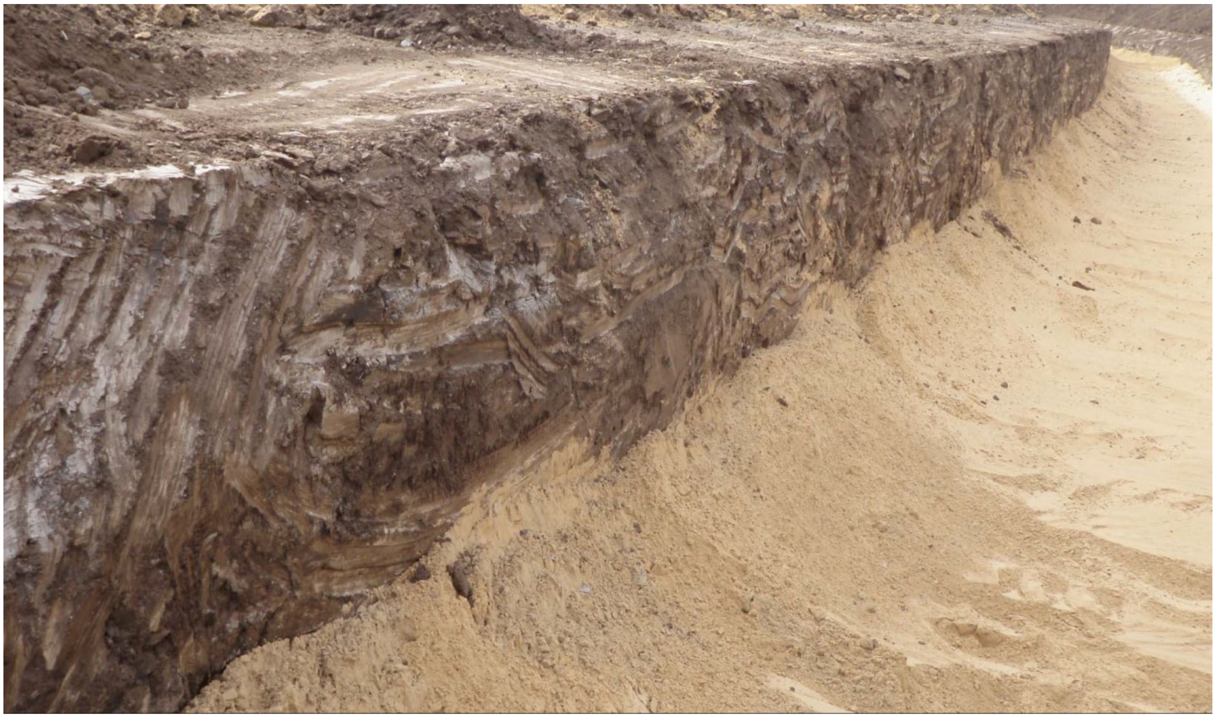

Figure 21. Chimney Drain Trench Excavation Exposing Compacted Lift (CNRL, 2018)

As part of the quality control and quality assurance plan, CNRL developed a procedure called a ‘Quality Assurance Density Test’, which was performed approximately twice weekly. The timing and locations are staggered based on fill placement rates to satisfy that the test pits achieve a representative spread across a lift. Following lift placement and a field density test, a test pit is dug in the location of the field density test. Additional density testing is performed at depth and proctor samples are taken in increments (J. Obrigewitsch, personal communication, December 15, 2017). The procedure served to supplement field observations with test data.

Test pits are excavated in incremental depths, with in-situ density testing performed at each interval to evaluate the degree of compaction through the entire thickness of lift. Figure 22 provides a representative example of this evaluation method, using data from a test pit trial conducted through a 5 m thick lift in Zone 5, compacted with 330T haul trucks (Thurber, 2005).

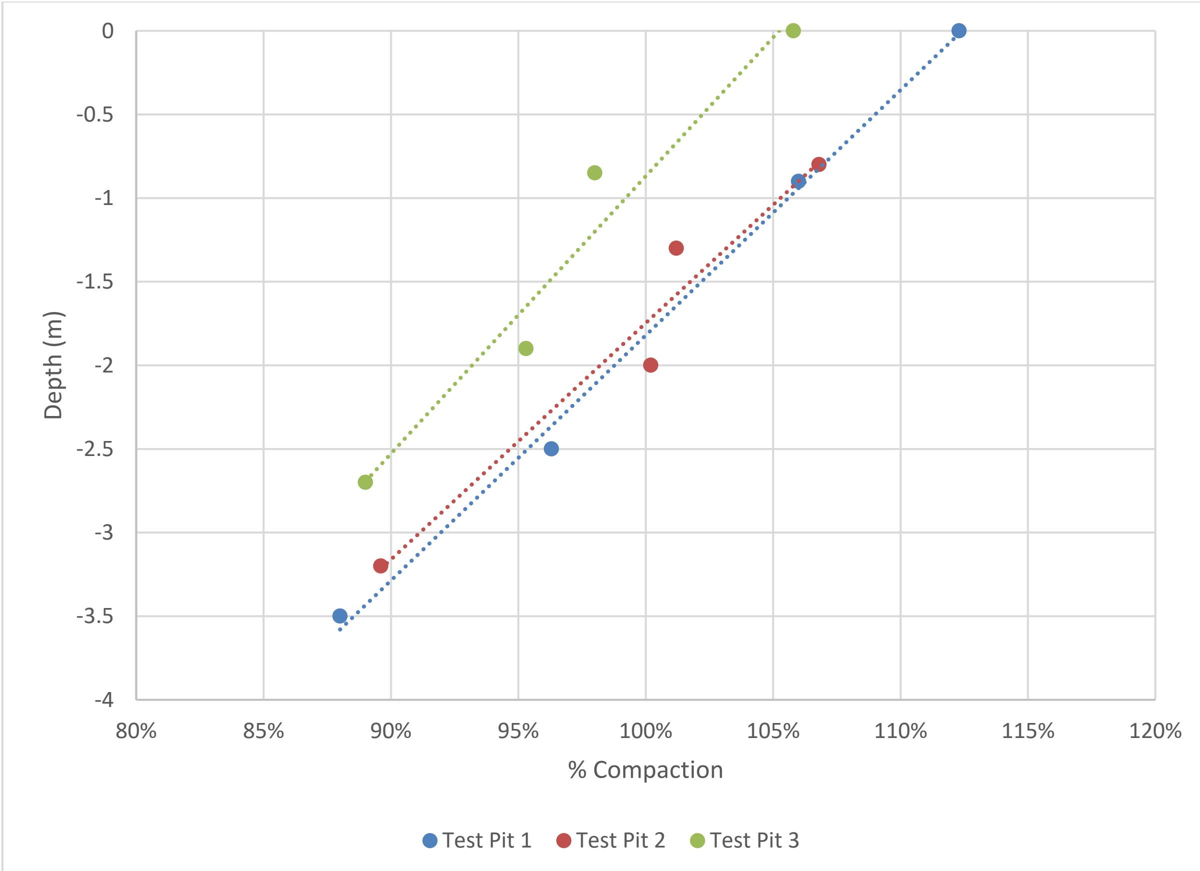

Figure 22. Percent Compaction vs. Depth from a Compacted Lift (Thurber, 2005)

The figure shows that at surface the percent compaction is greater than 100% of SPMDD and decreases linearly with depth through the lift. The linear trend can then be used to estimate the percent compaction at the bottom of a lift, given a known density at surface. This behavior may vary depending on soil type, as well as the amount and type of compaction applied. Therefore, for this method to be effective, it must be validated whenever one of the given parameters change.

3.6.4.2. Density Field Testing

Observational control methods such as rut and roll testing is routinely performed on a compacted lift as part of the approval process. The site criteria mandates that there shall not be more than 0.3 m of deviation in height, compounding both the rut and roll deviation. Rut and roll testing provides a quick evaluation of compaction and identification of soft or otherwise deficient areas. It is particularly useful for identifying materials placed with high bitumen content, which tend to behave as a high plastic clay.

Density tests by way of nuclear densometers, are performed approximately every 75 m x 75 m area of material placed (T. Adebayo, personal communication, September 30, 2015). However, the tests are performed on the surface of the lift, indicating that only the upper 0.3 m of the lift is evaluated. As a result, this test data must be scrutinized with caution. The test may not be entirely representative of the lift density but gives indications of material type and the effectiveness of compaction. It can be used as a tool to identify trends or problem areas of low density fills.

Proctor samples provide density, bitumen and moisture content values, as well as provide a vague characterization of the type of soil being placed. They serve as a verification of density test results and field observations. Proctor samples are collected as part of the 'Quality Assurance Density Test' and on an as-needed basis, such as when abnormalities or new materials from the pit are encountered (J. Obrigewitsch, personal communication, December 15, 2017). Samples are taken at the location of density tests to support the correlation of Proctor results and in-situ densities.

In the earlier stages of fill placement, Proctors used to be taken monthly, but were later increased to a weekly frequency to improve the response time for poor results and advance the understanding of materials being placed. The increased frequency allowed for better control over materials being delivered to site and prevent the costly impacts of removing fills failing to meet specifications (W. Abeda, personal communication, September 30, 2015). However, as the project has progressed, the understanding of materials has improved, and a broad range of proctor curves have been developed for the in-place fills.

3.6.5. Evaluation of Compaction Data

Standard Proctor based compaction criteria is specified. Two main issues arise when applying Standard Proctor testing to the construction methods used at Dyke 10. 1) The difference in compactive energy applied using 400-Ton heavy haulers compared to a Standard Proctor test, and 2) the volume and variability of fill types with their corresponding compaction curves.

First discussing compactive energy, the method of compaction has a direct impact on the compaction curve (Terzaghi, et al., 1996), The compactive energy applied by a 400-Ton heavy hauler is not well represented by the significantly less compactive energy applied for a Standard Proctor test.

CNRL performed a series of trials comparing Standard and Modified Proctor tests on the compacted fills but were not made publicly available. The trials found that the compacted fills tend to behave within the Modified Proctor range, i.e. 110% compaction, but with highly variable moisture contents. As shown Figure 23 and Figure 24, in-situ moisture contents can range from 4% to -10% deviation from optimum moisture content for the respective proctor test. A greater variability can be observed in Zone 2 due to the Clearwater fills. The result is a poor correlation between in-situ moisture content and the optimum moisture content as derived from a Standard Proctor test.

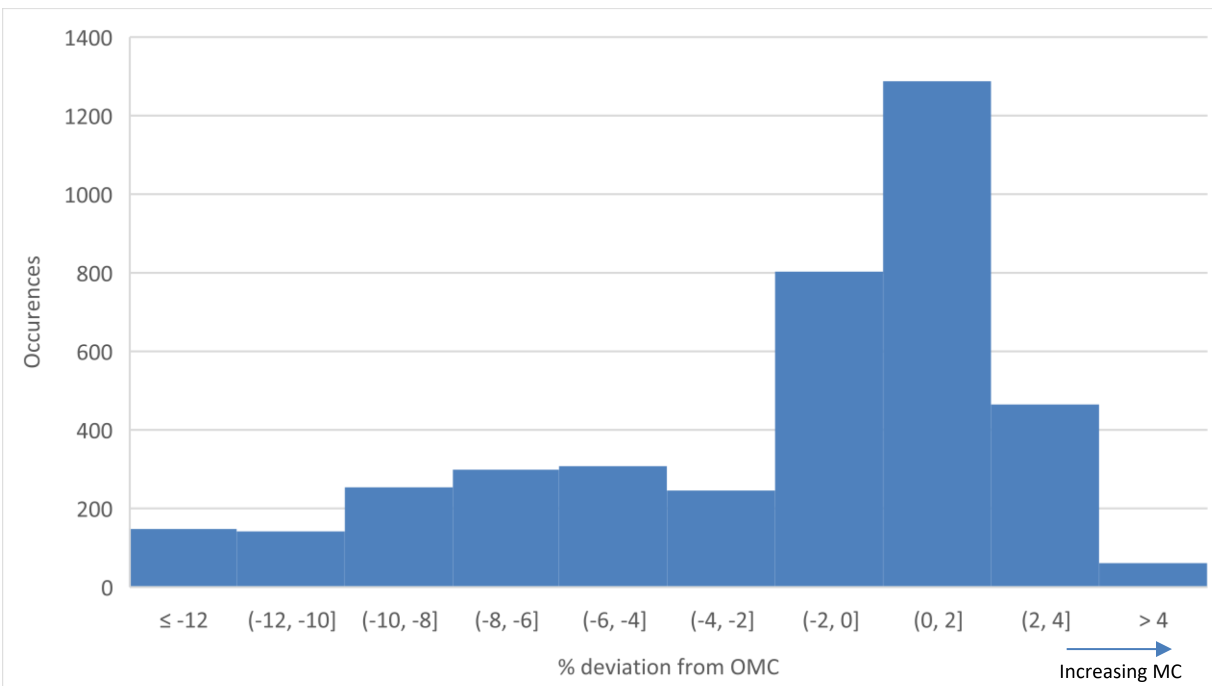

Figure 23. Percent Deviation from OMC for Zone 1 Field Moisture Contents (CNRL, 2015)

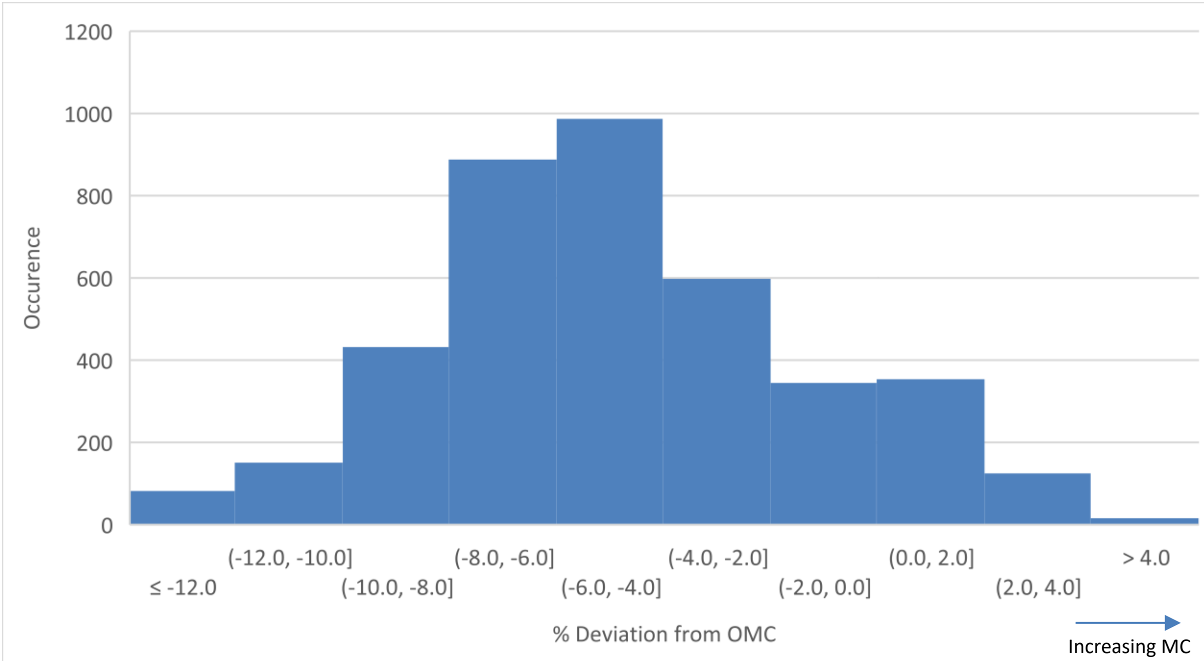

Figure 24. Percent Deviation from OMC for Zone 2 Field Moisture Contents (CNRL, 2015)

Addressing the second point, multiple soil types can be delivered to the push front of a lift due to the variability of materials encountered in the open pit. Face raking of the headwall with a 50 m^3 volume shovel bucket in the open pit permits material from multiple facies to be collected in one pass. Further variability is introduced by the capacity of 400-Ton haul trucks transporting material from multiple locations within the pit.

As the use of Proctor tests to evaluate of compaction is common practice, the challenge lies in determining an appropriate Standard Proctor Maximum Dry Density (SPMDD) to represent the materials placed. Compaction curves will differ between material types (Das, 2005) and sufficient testing to accurately represent the varied types of fills on site, is prohibitively difficult to achieve.

This effect is shown in Figure 25 and as per discussion with site personnel, there is a greater variability in density values acquired from Standard Proctor tests near the beginning of the project. This could be interpreted as being due to the greater variability of materials removed from the upper layers of the geological strata in the pit. Trends of consistent density values over long periods of time indicate the sourcing of fill from consistent geological units within the pit.

Multiple trends over the same time can be correlated to hauling taking place from multiple discreet locations in the pit simultaneously.

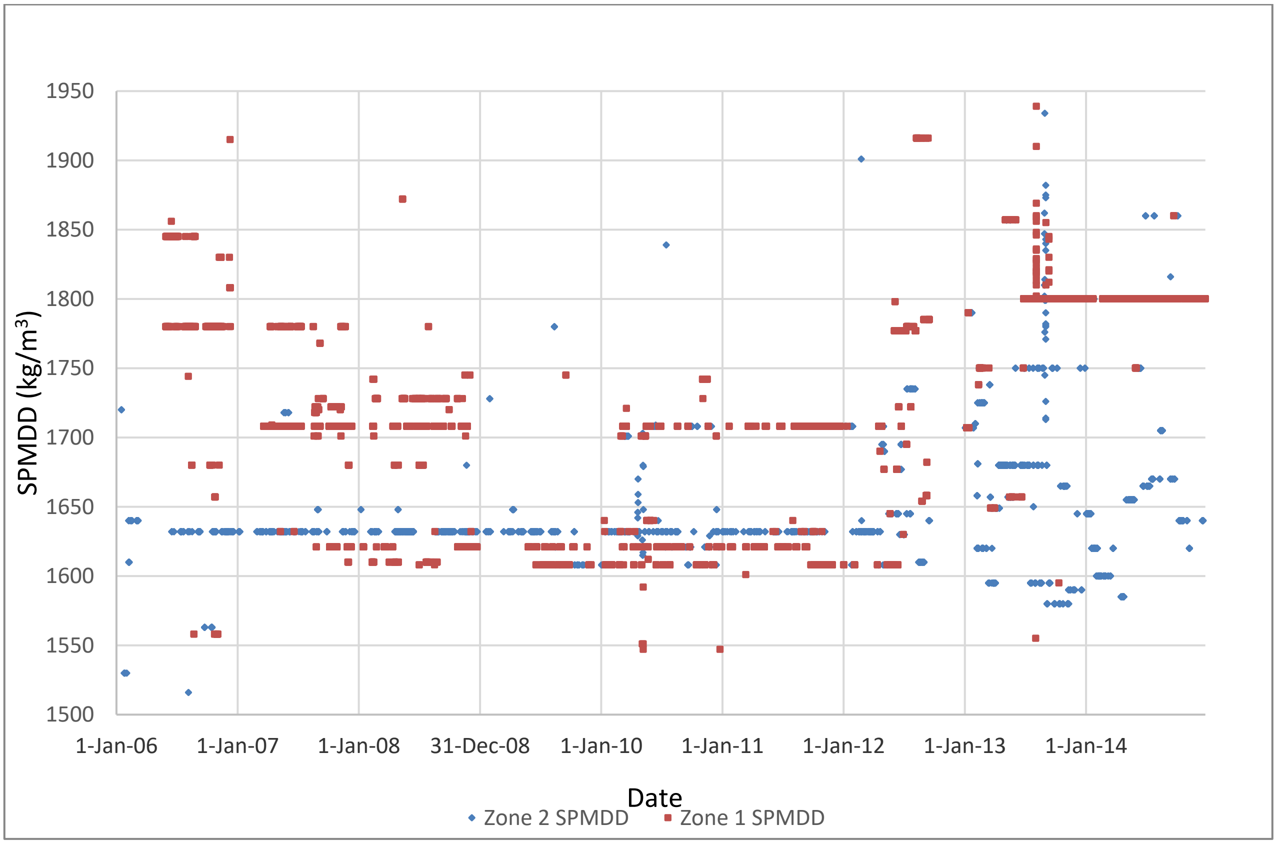

Figure 25. Zone 1 and Zone 2 Fills SPMDD vs Time (CNRL, 2015)

To standardize the quality control measures and implement a tighter control on a critical fill type while encountering a broad range of material types, a minimum specified density for Zone 1 fills was established in 2013, as identified in Figure 26 and Figure 27. This effort was supplemented by having access to more consistent borrow sources within the fully developed pit. The minimum specified density for Zone 1 fills was set at 1800kg/m^3, developed from a higher bound average of the SPMDD based on Proctor testing (J. Obrigewitsch, personal communication, December 15, 2017).

To evaluate the percent compaction necessary to support a minimum specified density, trials were performed evaluating the degree of compaction through the entire thickness of lift. Test pits were excavated in incremental depths, with in-situ density testing performed at each interval, using the methodology identified in Chapter 3.6.4.1. The specified percent compaction was increased from 95% to 100% at surface, which correlated to a density of 95% at the base of a compacted Zone 1 or Zone 2 lift.

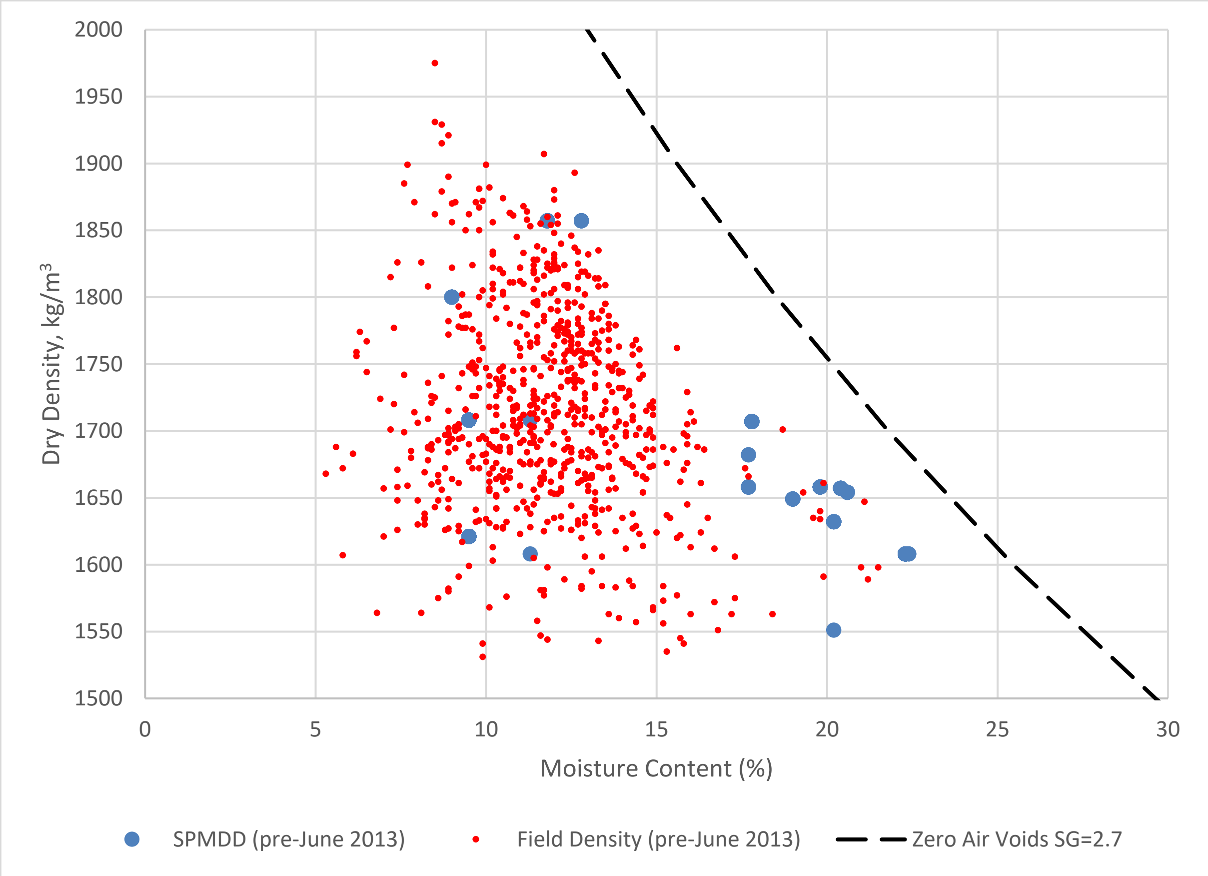

Figure 26. Moisture-Density Profile for Z1 Compacted Fills, pre-June 2013 (CNRL, 2015)

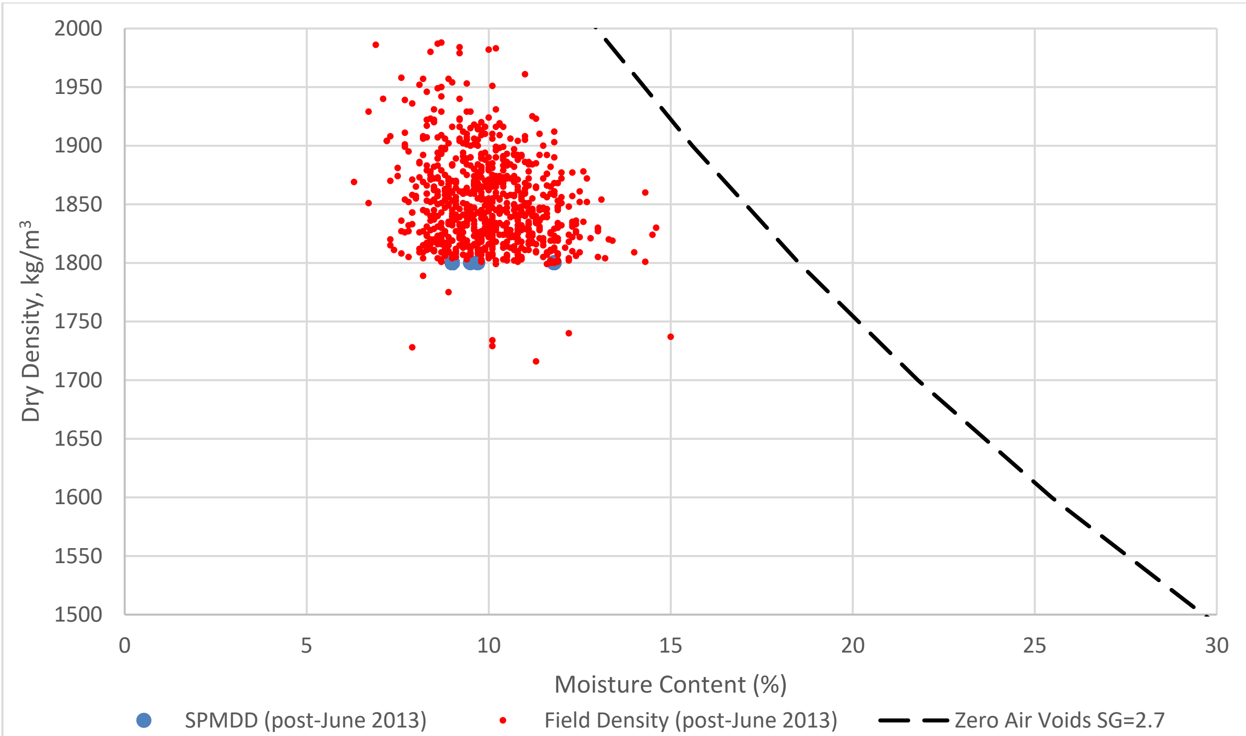

Figure 27. Moisture-Density Profile for Z1 Compacted Fills, post-June 2013 (CNRL, 2015)

Utilizing a minimum specified density, Proctor tests become less of a tool to measure compaction and more of a method to broadly evaluate fill types. For example, if an area of fill within a lift has undergone compaction but fails to achieve the minimum specified density, a proctor sample could be taken. If the results of the proctor indicate that the SPMDD of the material is less than 1800kg/m^3, which indicates that the material type is not sufficiently dense to satisfy the design criteria for the fill zone. Ideally this type of screening is captured by inspectors at the headwall or during placement, to minimize production delays due to the time to receive the test results and remediate.

Evaluating compaction of Zone 2 relies on a collection of Proctor curves to model the broad range of soils accepted for Zone 2, including Clearwater formation sources, as shown in Figure 28. When consistent fills are delivered from the pit, a rolling average of SPMDD is used. If a change in material type is identified, samples will be taken to correlate to the appropriate Proctor curve.

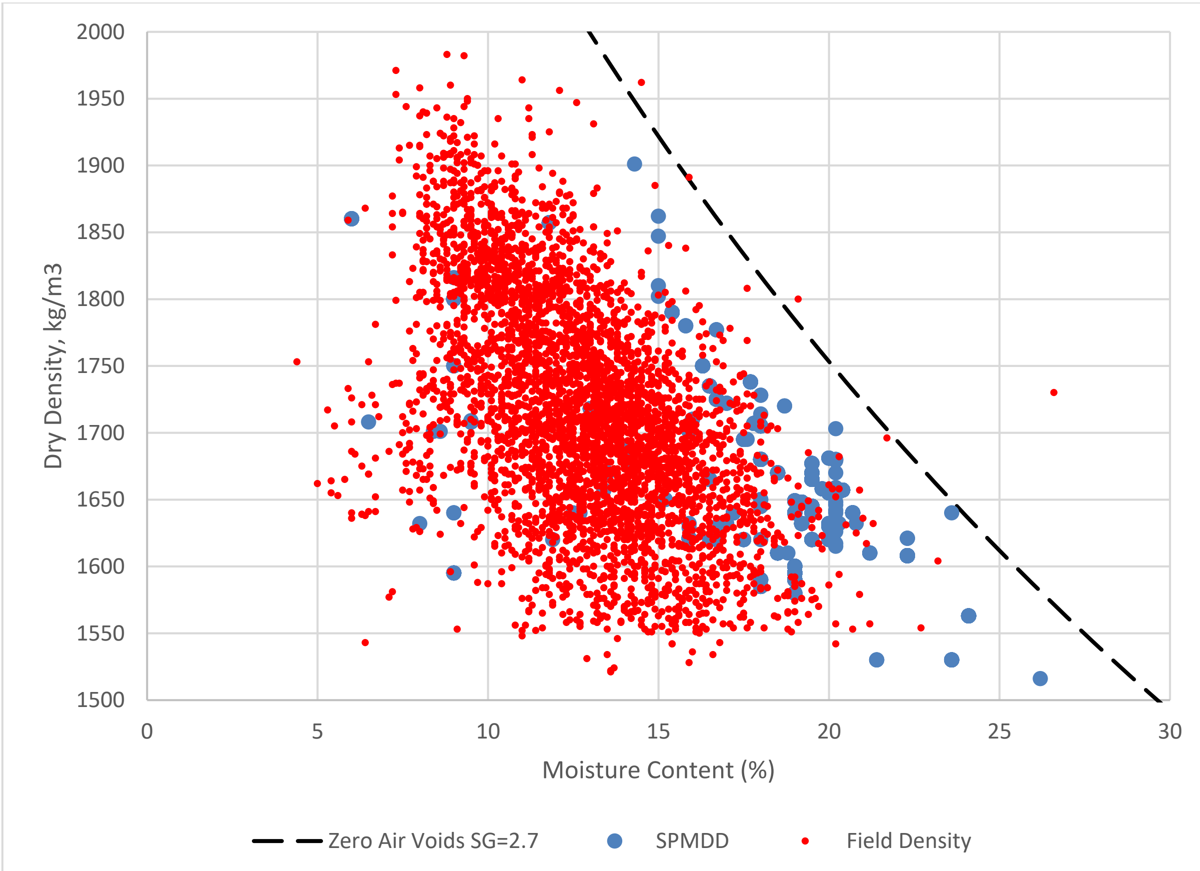

Figure 28. Moisture-Density Profile for Z2 Compacted Fills (CNRL, 2015)

3.7. Instrumentation

An extensive instrumentation program exists for the construction and operation of Dyke 10; however, the data was not made available for publication. The following provides a summary of the available information regarding Dyke 10's instrumentation program (W. Abeda, personal communication, September 30, 2015).

The instrumentation program services the design assumptions as part of the observational method. Focus is given to monitoring foundational stability, which is beyond the scope of this thesis. However, instrumentation installed in the dyke fills provide the necessary information to evaluate the dyke performance compared to the original design assumptions.

There are 500 to 600 instruments distributed across the dyke footprint, consisting of some of the following: 1) Piezometers – evaluate water levels and pore pressure response in foundation and fills; 2) Inclinometers – monitor deformation in foundation and fills. 3) Thermistors –

monitor fills sensitive to freezing (filter sand). Instruments are replaced or added as necessary, responding to the evolving needs of the instrumentation program.

The monitoring system for these instruments function with limiting parameters based on the location and material the instrument is located in. If the instrument response is beyond an allowable limit defined by design, an alarm system is triggered to inform the engineering team. The subsequent action is determined on a case by case basis but can generally consist of a stoppage of work in the affected area, an assessment of the issue, implementation of the required remedial effort, followed by a continuation of work.

The instrumentation program and monitoring system has been used to identify where deformations in the foundation or fills are either prone to, or have, occurred. The necessary stabilization programs can then be implemented to mitigate further deformation (Sisson et al., 2012). The stabilization programs may consist of the construction of a buttress or shallowing of a slope. The resulting application of the observational method permits the designers to actively respond to technical concerns, while minimizing over-conservative design assumptions.

4.0 Conclusion

To summarize, CNRL's Dyke 10 at the Horizon Oil Sands mine was used to illustrate how construction and quality control methods for oil sands overburden tailings dams differ from conventional dams.

The Horizon Oil Sands lease has a high overburden stripping to ore ratio, producing significant volumes of highly variable waste. The management of overburden waste requires a comprehensive understanding of the geological block model combined with collaborative mine planning and an effective dispatch system is necessary to manage the mobilization of up to 350,000 m^3 of fill per day. Dyke 10 has been designed in a robust manner to accommodate a broad range of fill types comprised of overburden waste from the mine, thereby reducing the need for storage of overburden elsewhere.

A combination of method and performance based specifications are used at Dyke 10. The method based controls and their management are built upon industry experience yet are expanded upon with modern technology and equipment resulting greater rates of production. Empirical methods such as test fills are used to evaluate potential borrow materials and develop the construction methodology and anticipated performance for each fill zone. Similar trials were performed for winter construction, establishing cold weather placement parameters such as the type of equipment required, exposure time limits, and cleaning requirements.

CNRL's quality control and quality assurance methods have had to adapt to the rapid rate of construction, by establishing a controlled system that is consistent, repeatable, and can hold up against scrutiny. The predominant quality control approach used at Dyke 10 is the reliance on detailed and well documented observations by qualified personnel. The observations are calibrated with periodic compaction density testing and laboratory index testing to both verify compliance with the specifications and verify that the qualitative controls remain representative of the materials placed. Training and education of construction personnel such as equipment operators and their supervisors serve as a significant component of the quality control system. Further redundancy is built in the system with internal audit inspections, along with monthly and semi-annual reporting to the design team and review board.

For Dyke 10, compaction to achieve a sufficiently dense and structure less unit across a placed lift is best evaluated via test pits, where the breakdown or complete embedment of dry blocky particles can be visually assessed along with the degree of compaction, then further corroborated with field density testing and associated proctor data. To address the tighter quality control required for the Zone 1 fill while receiving a range of material types, CNRL applied a high average minimum specified density for its core fill, Zone 1. This permitted a conservative yet representative method of evaluating the compacted fills, while reducing the degree of Proctor testing required. A range of Proctor curves is used for Zone 2, to accommodate the broad range of materials placed within this zone. Supplemental field testing is applied as necessary when conditions change.

While the quality control system described above has proven effective for the construction of Dyke 10, there are limitations. Where a design requires tighter controls such as narrow fill gradations, construction specifications may require an increased frequency of index testing. Scaling is a challenge, as one truck load of material for an oil sands overburden tailings dam may be an insignificant volume but could representative of an entire core width for a conventional dam. When establishing an appropriate quality control system, it's reliability is contingent on it being representative of the materials and construction methodology.

4.1. Recommendations of Future Research

The scope of this thesis is limited by the information made publicly available. Further learnings can be gained by providing further access to resources such as test fills, quality control plans, construction methods, instrumentation. Accessibility to this information can increase collaboration between operators, minimizing potential cost and effort spent learning experiences already acquired at other locations.

A similar study to this thesis can be applied to each of the active operators in the oil sands. The results of these studies can be compiled and the experiences learned shared between the parties. This can be used to optimize construction methods, designs and improve efficiency in quality control.

The incorporation of geotechnical parameters to the block model could be evaluated for its potential to improve the efficiency of optimizing material utilization for waste management and the classification of fills for dyke construction.

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