Horizon Dam Design, Construction and Quality Management

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ABSTRACT
Canadian Natural Resources Limited's Horizon Project is located approximately 70 km north of Fort McMurray, Alberta. Horizon Dam is a 30 m high structure constructed as part of the project. The dam is required to divert the Tar River around the tailings pond and to replace fish habitat as compensation for impacts of the mine and plant construction. The dam is a zoned earth fill embankment with a detached outlet and overflow spillway. This paper will discuss the following challenging aspects of the project construction that had to be overcome by Canadian Natural and their design consultants:

- At the time of tendering, contractors were busy. Therefore, Canadian Natural altered the project delivery model to use their own forces for the construction;
- The project required training equipment operators who would, in the long term, be used in the mining operation. The skills and techniques appropriate for mining are not always applicable to a 'conventional' civil construction project, and specifications and construction procedures were modified to accommodate these differences;
- The borrow sources were typically wet of optimum, and the summer construction season was often rainy, minimizing the opportunity for moisture conditioning of fine grained materials; and
- Movement became evident in the foundation during construction, requiring changes to the design and the construction schedule to allow completing the construction, along with deformation analyses to demonstrate adequate long-term stability.

RÉSUMÉ
Horizon projet de Canadian Natural Resouces Limited se trouve environ 70 km au nord de Fort McMurray, en Alberta. Horizon barrage est une structure de 30 m de haut, construite dans le cadre du projet. Le barrage est requis de détourner la rivière bitumineux autour de l'étang de résidus et de remplacer l'habitat du poisson comme une compensation pour les impacts de la mine et de construction de plantes. Le barrage est un talus de remplissage de terre zoned avec une prise détachée et le déversoir de débordement. Ce livre aborderons les aspects suivants difficiles de la construction du projet qui devaient être surmontés par Canadian Natural et leurs consultants de conception:

- Au moment de l'appel d'offres, entrepreneurs étaient occupés. Par conséquent, Canadian Natural modifié le modèle de livraison de projet à utiliser leurs propres forces pour la construction;
- Le projet requis la formation des conducteurs de matériel qui seraient, à long terme, utilisés dans les opérations minières. Les compétences et les techniques appropriées pour l'exploration de sont pas toujours applicables à un projet de construction civile «conventionnelles», spécifications et procédures de construction ont été modifiés pour prendre en compte ces différences;
- Les sources d'emprunt étaient généralement humides d'optimum et la saison de construction a été souvent pluie, minimisant l'occasion pour le conditionnement de l'humidité des matériaux correctement grainé ; et
- Mouvement devint évidente dans la fondation pendant la construction, nécessitant des modifications à la conception et la planification de la construction pour permettre l'achèvement de la construction, avec des analyses de déformation pour démontrer la stabilité à long terme adéquate.

1 INTRODUCTION

Horizon Oil Sands is located about 70 km north of Fort McMurray in northeastern Alberta's Regional Municipality of Wood Buffalo, as shown on Figure 1. Canadian Natural Resources Limited (Canadian Natural) produced first oil in February 2009 for a phased project with plans to produce a minimum of 270,000-bbl/d of bitumen. Their on-site upgrader that processes the oil sands bitumen is currently operating with a capacity of 110,000 bbl/d of marketable crude oil products, with planned expansion to produce a minimum of 232,000 bbl/d.

Mining operations generate tailings that must be permanently stored. An external tailings pond (Pond 1) provides out-of-pit storage of tailings during the initial years of the operation. The tailings pond is formed on three sides by a constructed earth dyke, and by natural high ground on the fourth (west) side. The Tar River and associated tributaries currently flow through the footprint of Pond 1, and must be diverted around the pond to manage water inventory in the pond. The diversion facilities consist of a dam, associated outlet works, and a diversion channel for southern tributaries to the Tar River. The mine development in the year 2010, Pond 1, and Tar River Diversion are shown on Figure 2.

The lower portions of the Tar River watershed are in the area proposed for mining and mine infrastructure. As well the upper portion of the Tar River watershed has to be diverted around the mine development and the Calumet River will be diverted in the future as mining progresses. Federal Regulations require compensation for alteration and loss of productive fish habitat. The lake formed by the diversion provides this compensation.

Horizon Dam is a 30 m high embankment dam that blocks the Tar River and raises water levels to allow cost-effective outlet channel construction and to meet the lake requirements of the compensation plan. This paper describes the design, construction and unique characteristics of the quality management system used during construction of the dam.

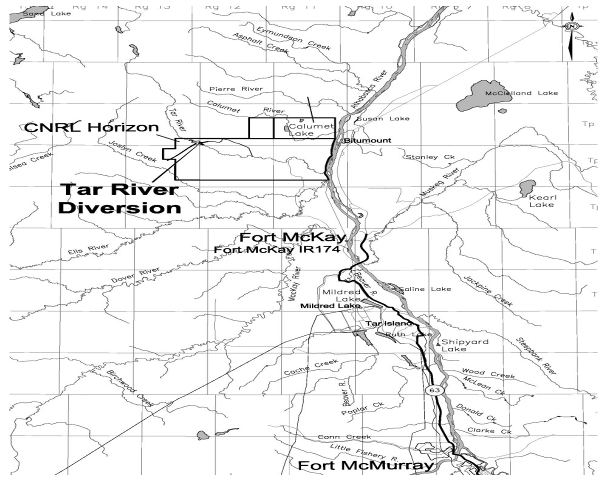

Figure 1. Location Plan

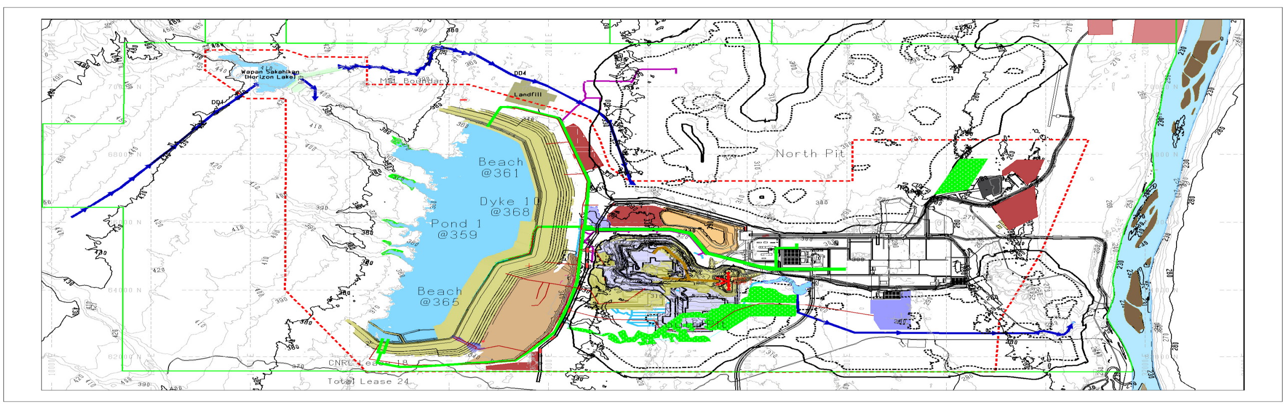

Figure 2. Tar River

2 SITE DESCRIPTION

The Tar River diversion site is located at a natural constriction in the Tar River Valley, located on the west flank of the Birch Hills, which rise relatively gently to the east.

2.1 Topography

The Tar River is incised over 30 m into the surrounding topography at the dam site, with the south valley wall being noticeably flatter than the north valley wall. The Tar River discharges to the Athabasca River, located about 18 km east of the dam site.

2.2 Geology

The stratigraphy outside the Tar River Valley generally consists of 5 to 10 m of Pleistocene glacial deposits overlying Cretaceous bedrock. Glacio-fluvial and alluvial deposits up to 6 m in thickness overlie bedrock in the base of the Tar River Valley. Bedrock at the site consists of the Clearwater (Kc) formation capped by the unconsolidated sand of the Grand Rapids (Kg) formation in the valley walls. At the dam site, the Grand Rapids has been completed eroded within the Tar River Valley, so that the bedrock surface in the valley bottom consists of the Clearwater formation. A geological cross-section showing the typical stratigraphy at the diversion location is shown on Figure 3.

2.3 Geotechnical Characterization

Glacial deposits at the site consist of till, glaciolacustrine clay, and glacio-fluvial sand deposits. The till is typically a very stiff, sandy, medium plastic clay till, with moisture contents that are typically slightly above both the plastic limit and the Standard Proctor optimum moisture content.

Glaciofluvial deposits at the site include clean, well sorted fluvial sands; silty, poorly sorted outwash sands; and fluvial gravels.

The Tar River Valley overburden, which is typically 5 m to 6 m in thickness, generally comprises river alluvium and overbank silt and clay deposits. The alluvium generally comprises sand and gravel with variable fines content. The overbank deposits are typically soft, silty clays with high moisture contents.

The Grand Rapids formation is a typically dense to very dense, silty, fine-grained sand. Much of the deposit is not significantly cemented, but occasional cemented zones are encountered. Based on the grain size distribution and falling head tests, the permeability of the formation appears relatively low, on the order of 10^{-6} m/s.

The Clearwater formation is a marine formation, generally comprised of clay shale with interbeds and interlaminations of silt and sand. Although the clay shale is typically hard to very hard, extensive preshears are commonly found along the bedding planes of high plastic layers. The high plastic layers have very low residual friction angles and typically develop high pore pressure in response to loading. As a result, they form preferential failure planes for slopes and embankments.

3 DESIGN SUMMARY

The dam was designed using the observational method to deal with unavoidable uncertainty that is associated with geotechnical design, especially because a clay shale

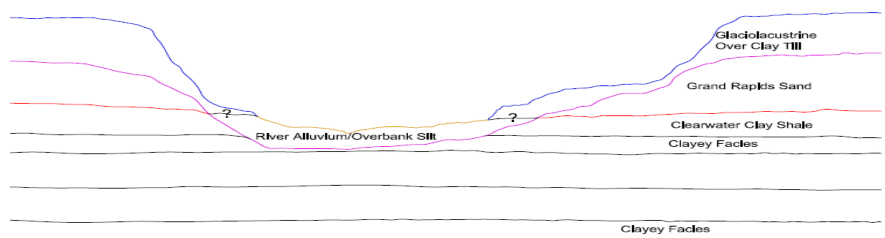

Figure 3. Cross Section across the Tar River Valley

(Clearwater) foundation is involved. The observational method is based on developing contingency plans so that changes can be implemented during construction should monitoring indicate they are necessary. This method balances economy and assurance of safety. It requires appropriate contingency plans, levels of surveillance, instrumentation, and performance monitoring as well as involvement of the design team in the construction approach. Contingency plans were identified that could be implemented if unfavorable performance was detected by monitoring during construction and operation. Key design criteria were:

- Because the Tar River Diversion dam is designed to protect the Pond 1 tailings dyke, which is immediately downstream, against floods and the dyke is a very high consequence structure, the dam was designed to handle the Probable Maximum Flood according to Dam Safety Canadian Dam Association (CDA) guidelines;
- Factors of safety against slope and foundation instability were selected in accordance with CDA guidelines; and
- The dam, including foundation and abutments, was designed to be capable of withstanding all seepage conditions and retaining the reservoir with appropriate consideration for any cracking of the central core that could reasonably occur.

3.1 Embankment

In addition to the low strength foundation, the design was developed to address the following issues:

- Using local materials, essential for cost effective construction because of the remote site;
- The locally available sand has variable fines content, varying from about 5% to over 20%;
- Layers of the Clearwater clay shale known to be dispersive; and
- Limited availability of rock at the site and in the region.

The resulting embankment design employed upstream and downstream design slopes consisting of benched slopes with an overall angle of approximately

11.9 horizontal to 1 vertical (11.9H:1V) over a height of 30 m. A typical cross-section at the maximum section is shown on Figure 4. Key embankment zones were:

- A central, compacted clay till core with side slopes of 1H:1V and crest width of 5 m, along with till zones placed against the natural slopes downstream of the core to lengthen the seepage path through the Grand Rapids forming the abutments. All alluvial materials and the upper 1 m of bedrock would be removed below the core;
- A fine filter covering the downstream face of the core and tied into the abutments;
- A collector drain at the base of the fine filter leading to finger drains with pipes extending to the downstream toe; and
- The upstream and downstream shells; under the shells of the embankment, the treatment of the alluvium would consist of removing all organic soils,

3.2 Seepage Control Measures

The primary seepage paths of concern were through the alluvial materials at the base of the embankment and on the valley flanks, and through the Grand Rapids formation in the upper valley walls. The potential for cracks in the embankment core was also addressed. Key seepage control measures developed during the design for the Tar River Diversion consisted of:

- A central core of compacted clay till that extends to the bedrock surface, along with a core trench infilled with similar material extending a minimum of 1 m into the bedrock;
- A chimney drain/filter along the downstream side of the core connected to finger drains that channel water to the downstream toe;
- Drains along the base of the natural slopes downstream of the core, and
- Zones of till placed against the natural slopes downstream of the core.

4 EARTHWORK PLANNING

Sources for borrow materials were initially planned as follows:

- Core: Clay Till from a borrow area on the left abutment upstream of the dam such that the borrow area would become part of the lake;
- Shell: Material other than clay till from required excavations such as the embankment foundation, diversion channel, outlet works, and lake expansion areas;
- Rip-rap and Bedding: From gravel pits about 20 km east of the dam site.

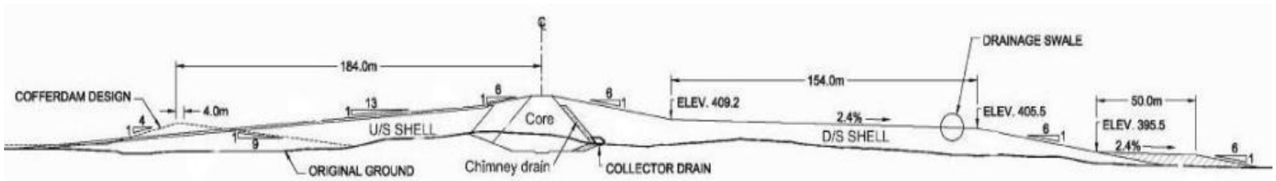

Figure 4. Initial Design Embankment Cross-Section

The bulk of the original design embankment consisted of compacted clay till in the central core and erosion resistant zones and compacted miscellaneous fill in the shells. Key specifications for embankment construction are shown on Table 1. The specifications also required that no frozen soil would be placed or have fill placed on it.

5 CONSTRUCTION EXECUTION PLAN

Construction was originally planned using a conventional design-bid-build approach. The project was tendered in July 2005. At this time, Alberta contractors were very busy, and bid prices significantly exceeded the owner’s budget. Therefore, Canadian Natural altered the project delivery model to use their forces for mass earthwork construction. Thus, the owner assumed direct responsibility for safety, quality, schedule, and cost of the project. The owner’s engineering staff acted as the construction engineer of record, with the assistance of consultants who had developed the design. Specialty contractors were employed for outlet structures and embankment finger drains, where mining techniques and equipment were not considered suitable.

Self-construction provides the owner with flexibility to change the design or work procedures during construction when appropriate, while avoiding disputes over the costs of changes and additional work. The cost savings associated with improving the efficiency of work procedures accrue directly to the owner. The owner can choose an acceptable risk level as long as regulatory requirements are met, and again it is the owner that accrues the full benefits of appropriately managed risks (such as potential for increased maintenance). In this instance, self-construction also allowed the owner to train construction forces that would be used for subsequent mining activities.

Self-construction presents challenges to the design consultants that are significantly different than those in design-bid-build projects. The consultant does not share in the gains that accrue to the owner. Nevertheless, the consultant is likely to be responsible for identifying and communicating the risks associated with changes to the design or specified work procedures. To effectively manage the liability associated with this responsibility, a thorough quality management plan must be implemented. Key ingredients of the plan are that:

- The consequences of risks must be identified not just qualitatively, but quantitatively;
- The probability of adverse consequences must be clearly described;
- Risks must be communicated to authority levels in the owner’s organization that are commensurate with potential consequences; and
- All decisions must be carefully documented.

In addition to the formal quality management plan, the process requires both trust and respect between the owner and their independent consultants. It is also important that both owner and design consultant are satisfied with contractual terms and conditions.

6 QUALITY MANAGEMENT SYSTEM

For construction of Horizon Dam, all involved recognized the need to develop a quality management system that was appropriate for the construction execution strategy. The objective of the system was to manage quality so that all project components:

- Contained the required attributes and features to meet, or exceed, the owner's requirements for safety, reliability, performance, operation;
- Complied with all regulations and approval conditions that apply to the project; and
- Identified and communicated risks to the appropriate entity.

Terminology for quality management appears not to be used or understood in a consistent manner. For this project, "Quality Assurance" is defined as an integrated system of management activities involving planning, implementation, assessment, documentation, reporting, and quality improvement so that a process, product or service is of the type and quality needed and expected by the project owner. "Quality Control" is defined as the actual hands-on activities such as inspections, examinations, and testing that take place to confirm that quality has been attained. Two key documents were developed; A Quality Management Plan (QMP) to describe the system, and an Inspection and Testing Plan (ITP) to describe the activities.

Although the International Organization for Standards provides a general body of reference for quality management, the authors are not aware of concise and readily available reference materials for preparing a QMP and an ITP. Based on the combined experience of the owner and design consultants, a construction QMP was developed that clearly defined roles and responsibilities for achieving quality requirements, and describing requirements for:

- Developing written work plans that conform to project drawings and specifications and having procedures for proposing and authorizing modifications to the plans as necessary based on results of quality control testing and inspections;
- An Inspection and Testing Manual for performing Quality Control testing, monitoring and inspections according to defined plans and methods, both to confirm that the work is in accordance with approved drawings and specifications, and that the actual field conditions are consistent with those assumed in design;
- Procedures to resolve disputes about construction quality in a timely fashion;
- Reviews and audits to confirm conformance with the testing and inspection methods;
- Documentation and reporting of non-conformances and actions taken to resolve the non-conformances;
- A strategy for continuous improvement of the construction activities and the Quality Management Plan; and
- Communication Strategy.

6.1 Project Organization

Responsibility for constructing the project resided with the Mine Manager. His responsibility was to meet the business need of the company to safely complete the project so that it was fit for use, cost-effective, and on schedule. This responsibility required balancing concerns that sometimes conflicted. To assist the Mine Manager in balancing concerns during project construction, three major groups were identified:

- Design and Quality Management;
- Construction Operations; and
- Construction Engineering.

The Quality Management Plan described responsibilities for members of each group in detail. Clear identification of roles and responsibilities is considered a key requirement for successful project management.

6.2 Work Plans

Central to quality control for the project was the development of activity-specific work plans that included provisions for construction in accordance with approved drawings and specifications. A constructability review was conducted for critical construction activities, attended by the construction, operations, and quality teams. Work plans were then developed by the construction operations group provided the following information:

- Description of work;
- Detailed step-by-step execution method;
- Equipment and Manpower required;
- Schedule Requirements;
- Budget;
- Quality Requirements and Inspection Program including witness points, and,
- Copies of applicable Field Level Risk Assessments (FLRA), drawings, and permits.

Where required, the work plan was subjected to careful field trials when they were first implemented; quality control testing was also planned to confirm that the work was in accordance with approved drawings and specifications. Once a work method was established that achieved satisfactory results, inspection activities focused on confirming and documenting that the construction method was consistent with the established plan, along with

Zone	Description	Minimum Standard Proctor Density	Moisture Content Limits [1]	Maximum Lift	Minimum Placement Temperature
1A	Core	>95%	-2% to 1%	200	-5°C
1B	Downstream abutment blanket	>95%	-2% to +2%	300	-5°C
2A	Shell	>95%	-2% to +2%	300	-20C
2B	Upstream random zone	>90%	-2% to +3%	400	-20C

(1) Relative to Standard Proctor Optimum Moisture Content

Table 1 Fill Placement Specifications

confirmatory quality control testing.

6.3 Inspection and Testing Manual

An Inspection and Testing Manual (ITM), was developed to document and describe the tactics and the key activities for quality control. The primary audience for the manual was field engineering staff. The contents included:

- A summary of the risk management strategy for the project;
- Qualifications of personal to perform inspection and testing tasks;
- Testing methods, protocols, and frequency;
- Requirements for assessment and communication of test results;
- Documentation and reporting required for test results;
- Attitude and communication techniques required for successful dispute resolution; and
- Witness points where field presence of designers was essential prior to further construction

6.4 Dispute Resolution

Disputes are a natural consequence of competing requirements to manage cost, schedule, quality, and safety. Provided that disputes are managed in a professional and constructive fashion, disputes can lead to improvements in the overall result of the project. The fundamental process for resolution of disputes involving quality is to:

- Immediately communicate the competing requirements;
- Resolve the dispute by the appropriate person(s), as close to the operating level as practical and in a timely manner, with minimal involvement of senior management when possible;
- Document the resolution in a simple and clear manner, and
- Provide a defined path for escalation of the dispute when agreement cannot be readily reached. The authority responsible for the overall project, in this case the Manager of Mine Operations, is ultimately responsible for resolving disputes.

6.5 Quality Assurance Testing, Audits, and Review

A program of testing, reviewing, and auditing was implemented to confirm that the quality management procedures are followed, and to confirm the results of quality control testing. Many of the activities are typical for construction quality control, such as:

- Maintenance and calibration of equipment;
- Daily quality reports, along with summary reports at an appropriate frequently (weekly to monthly) and a project completion report;
- Independent testing;
- Supplemental testing (e.g., test pits to confirm clod breakdown, or laboratory permeability tests of filter sand to confirm assumed design values); and
- Auditing.

In addition, Canadian Natural formed the Horizon Mining and Geotechnical Review Board. The Board consists of independent industry experts, and meets twice yearly to review mine and tailings plans, operating procedures, and geotechnical designs. However, because the dam construction would proceed quickly relative to the meeting schedule of the board, a construction advisory team was established to review the work and provide suggestions for improving quality and effectiveness of construction methodology. The team provided an independent assessment to confirm that field conditions are consistent with design assumptions, and review proposed changes to the design and work procedures. The team consisted of three experts with considerable experience in dam construction. One member of the team was the lead geotechnical designer for the project, to provide background regarding design intent. Another member also sits on the Horizon Mining Geotechnical Review Board, and provides continuity with that review process. The third member has not been involved with previous Canadian Natural work, and was selected for experience and independence. The team visited the project at bi-weekly to monthly intervals during key periods of activity.

7 CONSTRUCTION ISSUES

Several significant issues were addressed during construction through the quality management system. Three of the most prominent issues are discussed in further detail to provide examples of the benefits and challenges of owner self-construction. The issues are:

- The foundation alluvium was observed to contain a significant portion of cobbles, increasing permeability and the potential for excessive foundation seepage under the proposed cofferdam;
- Fill that was generally wet of optimum was placed and compacted with a fleet including large (Cat 777) haul trucks; and
- Construction was delayed by wet summer weather and wet borrow conditions, leading to a temporary increase in the downstream slope in an attempt to complete critical earthwork prior to winter. Subsequently, movement on the weak bedrock was measured during construction leading to concerns about the impact of impoundment.

7.1 Foundation Seepage Control During Construction

The original cofferdam design, shown on Figure 5, recognized the existence of permeable alluvial deposits and relied on providing a sufficiently long seepage path in the foundation to meet minimum, empirical guidelines for acceptable performance. The plan for constructing the embankment core was to rely on localized dewatering of the core trench along with a contingency for pumping wells. During construction of the cofferdam, localized zones of gravel and cobbles with high permeability, shown on Figure 6, were observed in the foundation of the Tar River Cofferdam. Investigations undertaken to assess the foundation conditions and establish appropriate remedial measures confirmed the existence of permeable deposits with hydraulic conductivity up to four orders of magnitude higher than the average value assumed for design.

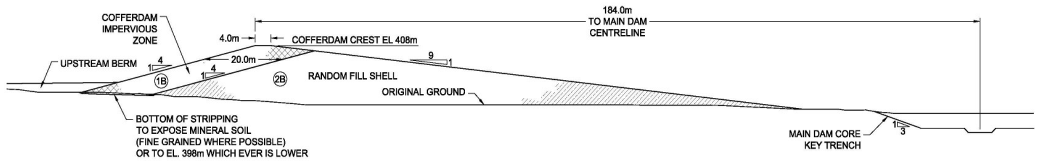

Figure 5. Cofferdam Cross-Section

The design review team expressed concern regarding high rates of seepage and high seepage velocities that could cause:

- Excessive seepage into the cutoff trench for the main dam, which may not be controlled by pumping, leading to foundation damage and flooding of the excavation; and
- Excessive uplift pressures under the cofferdam after the cutoff was completed, leading to seepage “blow-outs”, cofferdam instability, or both.

Based on the adverse foundation conditions encountered, and the lack of experience of the mining construction team with specialized dam construction, the seepage control design was modified. Two alternatives were considered: (1) construction of a slurry wall or (2) installation of pumping wells. Based on both the estimated cost and constructability considerations, the slurry wall was selected as the preferred alternative. The slurry wall also allowed eliminating the cutoff trench provided in the original design for the main dam

The use of a slurry wall required that the core geometry be changed so that it tied into the top of the wall. The central core was replaced by an upstream sloping core, as shown in Figure 7. To avoid placing additional fine filter and extending the finger drains, a vertical filter/drain was used in the original location and clay till was placed between the core and the filter/drain. Some sand layers were permitted in this zone.

Figure 6. Permeable Alluvial Deposits

The primary risk identified with the design change was that excess pore pressures would develop in the foundation under the downstream shell of the cofferdam after the slurry wall construction was completed, resulting in seeps, boils, or piping. In the event that these conditions were observed, the proposed mitigation was to install relief wells. In fact, seeps were observed. Due to heavy construction activity in Western Canada, drill rigs could not be procured rapidly enough to install the wells. Therefore backhoes were used to excavate sumps that were backfilled with drainage gravel. This measure proved successful in controlling the excess pore pressure.

This example illustrates how a change in understanding of actual site conditions was addressed quickly and cost effectively in a self-performed project. Risks were also identified and successfully and cost-effectively mitigated. When a contractor is involved, changes often involve premium rates, as the owner has little leverage for negotiation.

7.2 Fill Placement Using Large-Scale Equipment

Two Komatsu PC1800 excavators were the primary tool used for borrow excavation, with smaller excavators used for specialized work. Six Caterpillar 777 100 ton haul trucks were used for transporting material from the borrow area to the dam site, supported by up to eight 30 to 40 ton articulated trucks. The 100 ton trucks were selected because they were required to support future mining operations. Even the 100 ton trucks are considerably smaller than the 400 ton haul trucks used to mine ore for bitumen production. Civil dam contractors typically use trucks no larger than the 30 to 40 ton articulated ones, and the specifications were written based on the typical technique where the soil is dumped on a scarified surface, spread with a dozer and compacted with a pad foot roller.

Much of the fill available for the construction of the Horizon Dam was relatively wet. Moisture conditioning of the fill to consistently meet target moisture contents was impractical because of the prevailing climatic conditions and the short schedule available for construction. A review by the geotechnical designers indicated that the generally wet fill available for use in Horizon Dam was not detrimental to the likely long-term performance of the dam. Soil “clods” are likely to be broken down by compaction effort applied to fills wetter than optimum, especially considering the compaction effort applied by haul trucks. Within reasonable limits, wet fill materials tend to exhibit low permeability. Although wet fills may be of relatively low strength and are likely to develop elevated pore pressures in response to compaction and loading; these attributes cause the fill to be deformable to accommodate imposed strains and unlikely to support tensile stress necessary for cracking. The potential for embankment deformation was recognized, but was considered acceptable because of the flat embankment slopes. Although construction delays might be necessary if excessive embankment deformation was observed, moisture conditioning at the wet fill would have certainly delayed construction. By monitoring the lateral deformation and delaying construction only as necessary to achieve some control of the lateral deformation rates, the owner was successful in balancing the need for expeditious construction with the need to prevent excessive lateral deformations. The embankment deformation proved acceptable, thus benefiting the project.

The wet embankment fill, as noted previously, was a significant challenge relative to the support of the equipment used for construction of the Horizon Dam. Had the earthwork been performed based on a lump sum or unit rate contract, the potential for a claim due to the high fill moisture content is considered significant. The owner’s operations staff dealt with the difficult conditions by carefully planning borrow operations to select relatively dry material to construct temporary roads across the embankment and placement operations to place material in the most appropriate location. When necessary, the large haul trucks were partially loaded. Thus, while the wet fill presented challenges, operational solutions were identified that minimized costs incurred.

Earthworks construction at oil sands mines has long demonstrated that effective compaction can be provided by heavy haul trucks, particularly when traffic patterns are controlled to cover the entire fill surface. Experience has also shown that the compaction depth provided by heavy haul trucks is greater than conventional civil equipment. Therefore, a work plan was proposed to use the 100 ton trucks to achieve the required compaction and increase the lift thickness. Several tests were carried out using different lift thicknesses, different traffic patterns, and varying the number of passes. Test trenches to observe the fill and allow density testing were completed.

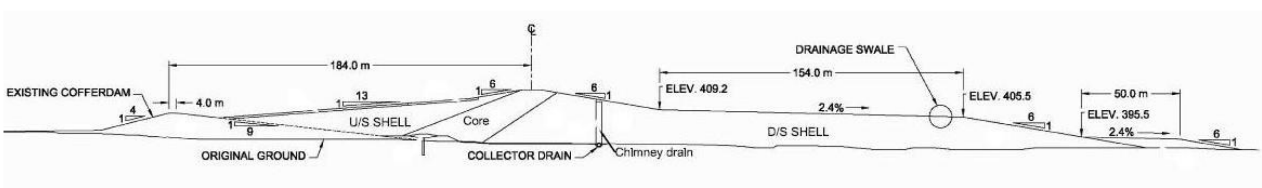

Figure 7. Revised Embankment Cross -Section

Lift thicknesses were doubled to 400 mm for Zone 1A fill, and increased to 500 mm for Zone 2A fill. Zone 1A was the only material on the Horizon Dam for which some kneading compaction and measures to enhance lift bonding were required Therefore, compaction with a pad foot compactor was required for the fill surface prior to placing a subsequent fill lift. Hauling equipment was not allowed to travel on the Zone 1A fill surface after it was prepared to receive a new lift of fill. Pad foot compactors were not used except for the Zone 1A surface.

The risks identified with the change in compaction were a slight increase in the potential for seepage along imperfections between compacted layers and increased settlement of the embankment in the event that the bottom of the lift was not compacted in accordance with the design assumptions. Potential seepage would be mitigated by placing filters. The consequence of excess settlement were studied. Given that the probability of these consequences was relatively low, and that costs could be deferred until after the mine was operating, the risks were considered acceptable to the owner. Neither embankment seepage nor significant embankment settlement have been observed to date.

7.3 Foundation Performance During Construction

A known challenge of Northern construction is the combination of long winters and rainy summer seasons. It was recognized that constructing the main dam in a single season would require favorable conditions. In fact, the construction season was somewhat wetter than average. As the construction proceeded into the summer months, it became apparent that completion before the onset of winter was unlikely. The operations staff and equipment were required for other activities beginning the next year. Operations staff proposed building the central dam section ahead of the downstream berm so that the project could be completed on schedule. As placement specifications for the downstream fill allowed operating in colder weather than placement specifications for the impervious core, this would extend the construction season.

The design team identified the risk that the temporary steepening of the downstream slope might initiate foundation deformation. Instrumentation for the dam included inclinometers extending into the clay shale and foundation piezometers. The design team used the measured piezometric data and analyzed the proposed construction sequence. The analysis using most likely design strength parameters indicated that embankment stability would be acceptable, but analysis using reasonable worst-case parameters indicated stability would not be acceptable. The original design had been developed including the contingency for a downstream stabilization berm. The owner accepted the risk that the proposed construction sequence might require placing the downstream berm.

Significant lateral deformation was observed in the dam foundation starting in late August 2007. As a result, monitoring frequency was increased. From August 2007 to December 2007, monitoring indicated that the dam underwent lateral movements in the order of 300 mm and 50 mm at about 70 m and 280 m downstream of centerline, respectively. The movements, as they evolved, appeared typically to be concentrated on a shear plane near the bedrock surface. The lateral deformation appeared closely related to fill placement, accelerating when fill placement in the middle portion of the dam proceeded and decelerating when the fill placement was suspended near the middle of the dam. To reduce the potential magnitude of the lateral deformations, the rate of fill construction in the central portion of the dam was reduced and the fill placement efforts were redirected to the downstream toe. Some additional fill was added to the dam's downstream toe area as an extended toe berm.

Although the construction method employed may have contributed to the requirement for constructing the contingency toe berm, subsequent analyses of the embankment indicated that mobilized strengths were likely closer to the reasonable worst-case than the most likely case assumed for design, so the berm may have been required in any event. The revised method did allow constructing the middle off the embankment under summer placement conditions up to about the 100 year reservoir level. Winter conditions did exist when placing some of the downstream berm as well as the central section of the embankment above the 100 year operation level of the reservoir.

8 SUMMARY

Horizon Dam was constructed by the facility owner under challenging schedule and site conditions. Because it is unusual for an owner to construct a dam using their forces, an approach was developed to allow the owner to work with design consultants to address site and schedule challenges by modifying the design while appropriately identifying managing risk. Through this approach, in conjunction with the observation method, project costs were controlled and field issues were managed effectively. The approach for embankment construction was successful because:

- A quality management plan was developed that included a process for change management and construction issue resolution;
- Documentation of changes included an assessment of the associated benefits and risks that were agreed by all parties involved; and
- Experienced personnel were present at the construction site on a regular basis and worked collaboratively to identify solutions and manage risks.

By choosing to construct the project using their forces and by employing an effective quality management plan, the owner was able to successfully complete the project while developing operating procedures and training personnel, providing significant benefit once mining operations began. In addition, costs due to difficult and unforeseen site conditions were managed effectively without unnecessary escalation or claims. Despite challenging site conditions, the dam is performing safely through on-going application of observational methods.