Design and Construction of a Seepage Cut Off Wall Using The Slurry Trench Technique in Cold Temperatures at the Horizon Dam Project

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ABSTRACT
A seepage cut off wall was constructed in 2007 as part of the Horizon Dam project at Canadian Natural Resources Ltd. (CNRL) Horizon Oil Sands site. The Horizon Dam is an earth retention structure which diverts the Tar River around the mine and plant site, and creates a man-made lake providing replacement fish habitat. A cut off wall was necessary to control seepage through the native coarse grained alluvial deposits encountered under the dam and to minimize the risk of piping due to large hydraulic gradients created by the lake. A field investigation was conducted using various geotechnical drilling methods, geophysics and in-situ testing to support design of the cut off wall. Due to various design issues, a literature review and laboratory testing program was carried out to assess the appropriate backfill mix to be used. Construction of the cut off wall took place at the end of winter using the slurry trench technique. This resulted in unique constructability issues due to the cold weather, the use of cement in the backfill, and the native soil conditions. A quality assurance program was implemented during construction to assess if the design specifications were being met. This paper discusses the design issues and methodology, and the unique constructability issues that arose during construction.

RÉSUMÉ
Dans le cadre de la réalisation du barrage Horizon du projet des sables bitumineux d'Horizon du Canadian Natural Resources Ltd. (CNRL), un écran d'étanchéité a été construit en 2007. Le barrage Horizon est un ouvrage de retenue qui détourne l'eau de la rivière Tar autour des aménagements miniers et d'opérations, et qui crée un lac artificiel qui agit comme alternative pour l'habitat aquatique. Le barrage, fondé sur des dépôts alluviaux à grains grossiers, a nécessité la construction d'un écran d'étanchéité afin de minimiser des fuites à travers de la fondation, et de minimiser le risque de formation des renards dus aux forts gradients hydrauliques imposés par la création du lac. Les travaux de reconnaissance réalisés pour la conception de l'écran d'étanchéité ont consisté de diverses méthodes de forage, de sondage et d'essais in-situ. Des contraintes rencontrées pendant la conception de l'écran d'étanchéité ont requis une revue littéraire et un programme d'essais de laboratoire pour développer un matériau de remblayage adéquat. La construction de l'écran d'étanchéité s'est déroulée en hiver un ayant recours à la méthode de tranchée de boue ciment-bentonite, ce qui a entraîné des difficultés particulières causées par la faible température, l'utilisation du ciment dans le matériau de remblayage et les conditions de fondation. Un programme de contrôle de qualité a été mis en place pendant la réalisation de la tranchée pour s'assurer que les exigences des devis étaient rencontrées. Cet article présente la conception et la méthodologie employées, ainsi que les problèmes particulières rencontrées pendant la réalisation de l'écran d'étanchéité.

1 INTRODUCTION

The Horizon Dam was constructed as part of CNRL's Horizon Oil Sands Project located approximately 70 km north of Fort McMurray, Alberta.

The Horizon Dam is a zoned earth fill dam which diverts the Tar River around the mine and plant site, and creates a man-made lake providing replacement fish habitat. The dam is approximately 30 m high and 320 m long, with a footprint of over 400 m along the river valley.

To temporarily divert the Tar River around the construction site, an earth filled coffer dam and diversion channel were built upstream. The coffer dam would be incorporated into the main dam structure. Construction of the coffer dam was completed during the winter months of 2006/20007 when river flows were seasonally low and manageable by pumping (i.e. before the spring freshet).

This paper discusses the design and construction of the soil-cement-bentonite seepage cut off wall for the Horizon Dam using the slurry trench technique. Due to scheduling constraints, construction of the cut off wall was executed at the end of winter (March and April, 2007), which resulted in below freezing temperatures and inclement weather conditions, which required unconventional construction practices.

Reference is made to the paper in this conference by Patrick and Sisson (*2010)* which provides a more detailed discussion of the design and construction of the Horizon Dam.

2 SITE CONDITIONS

The site is located within the post glacial Tar River Valley, where the river meanders from northwest to southeast across the valley floor. The geology generally consists of recent alluvium and overbank silt and clay deposits, overlying Clearwater clay shale bedrock (Clearwater). Colluvium deposits occur near the base of the river valley walls, interbedded with the alluvium. The Clearwater Formation is a marine clay shale of Cretaceous age. It is over-consolidated and, using soil descriptor terms, has a hard to very hard consistency.

An extensive field program was completed in late 2006 and early 2007 to define the soil and bedrock conditions below the main dam. Due to the large contrast in geological conditions at this site, a variety of investigation techniques were used. The field program consisted of electrical resistivity tomography (ERT), test holes, field permeability measurements, and laboratory testing on soil and bedrock samples.

The ERT study "imaged" the top of the Clearwater relatively well due to the contrasting conductive properties with the overburden. The study approximated the overburden thickness across the river valley and helped in the selection of test hole locations for further investigation. Twenty eight test holes were drilled at approximately 10 m spacing along the alignment. Due to the coarse grained nature of the soils, a Becker Hammer drill rig was used to drill the test holes. Wet rotary coring and Lasky sampling were also used to investigate the bedrock. Wells were installed in select test holes to facilitate permeability measurements of the various stratigraphic units.

The results of the investigation showed the alluvium was composed mainly of loose sands and gravels, with frequent cobbles and boulders. Some clay layers were noted within the alluvium. The colluvium was mainly soft clays and silts, which were typically encountered near the left and right banks of the dam. The maximum overburden depth was 8.5 m and its width was 166 m at the cut off wall location. The measured bulk permeability of the alluvium ranged from $2x10^{-4}$ m/s to $8x10^{-4}$ m/s, while the permeability of the Clearwater was less than $1x10^{-10}$ m/s.

3 DESIGN

3.1 Overview

The preliminary design of the dam called for a compacted clay core extending down through the alluvium into the Clearwater. Pumping wells or conventional sump/pump systems were anticipated for use in dewatering the excavation through the alluvium while the core was constructed. The field investigations found the alluvial deposits more extensive and locally more permeable than originally thought. Since the coffer dam would be impounded prior to the clay core being excavated, the feasibility of dewatering the core trench excavation was uncertain.

The following seepage control options were evaluated: 1) Construct a temporary cut off wall using the slurry trench technique through the coffer dam prior to construction of the clay core for the main dam, and 2) Construct a permanent cut off wall using the slurry trench technique that would provide seepage cut off for both the coffer dam and main dam. A permanent cut off wall was chosen as the more advantageous method for cost and schedule reasons. A slurry trench was selected as the preferred construction method since the excavation is typically no wider than 1 m, and the slurry supports the trench walls from collapsing by counterbalancing the groundwater pressure.

3.2 Backfill Mix Design Requirements

The backfill for the seepage cut off wall must satisfy certain conditions and criteria. Design guidance was obtained from Bulletin 51 of the International Commission on large Dams (*ICOLD 1985*), as discussed in the following paragraphs.

The overall permeability of the cut off wall must be sufficiently low to prevent excessively high discharges. A permeability of $1x10^{-8}$ m/s or less was selected as being acceptable. The risk of hydraulic fracturing was not considered significant since the cut off wall was situated so that the horizontal and vertical stresses are larger than the water pressures at the cut off wall depth.

The cut off wall will undergo deformations due to the weight of the dam. Also, horizontal and vertical deflections will occur in the dam fill and in the foundation due to the weight of the dam and impoundment of the reservoir (*refer to Patrick and Sisson, 2010*). The cut off wall must endure deformations imposed upon it without significant cracking or loss of its seepage control function. An ideal backfill would have a similar stiffness to the surrounding soils. ICOLD recommends a Young's Modulus no greater than 4 to 5 times than that of the soil. Table 1 provides typical Young's Modulus values for the various soil types encountered at site. A target Young's Modulus between 25 and 100 MPa was selected for design.

Table 1. Typical Young's Modulus for Various Soil Types (*after Bowles, 1996*)

Soil	Consistency	Young's Modulus, E_s (MPa)
Clay	Very Soft	2 - 15
	Soft	5 - 25
	Stiff	15 - 50
Sand & Gravel	Loose	50 - 150

The cut off wall is not a structural component and therefore needs only to have sufficient strength to resist in-situ stresses at depth.

After construction of the final dam structure, the impounded lake will create hydraulic gradients (i) in the order of 30 across the seepage cut off wall. Since the alluvial deposits are relatively coarse, poorly graded and lacking in fines, the potential for internal erosion (piping) of the backfill material was considered a significant threat. To meet ICOLD requirements for internal stability, a binder agent was needed.

Backfill that meets the stiffness, permeability and internal erosion resistance requirements described above has not commonly been required or used in Alberta. To meet these criteria, cement was needed in the backfill. To achieve the appropriate strengths and Young's Modulus values, the cement-to-water (c/w) ratio of the backfill would actually be quite low compared to plastic concrete, ranging between 0.1 to 0.3.

3.3 Selection of Backfill

A literature review and laboratory testing program was conducted to provide an appropriate backfill mix design. Both cement-bentonite and soil-cement-bentonite backfill mixtures were investigated during the design stage. Unconfined Compressive Strength (UCS) and constant head permeability tests were performed for three c/w ratios (0.1, 0.2 and 0.3). Vertical and horizontal deformation measurements were obtained on the UCS samples while testing, which provided an indication of the Young's Modulus and Poisson's ratio. Figure 1 through Figure 6 present the applicable strength and permeability test results.

The effect of bentonite hydration on the performance of the backfill was also analyzed by preparing test samples using both non-hydrated and hydrated bentonite slurry. The tests showed that the bentonite must be fully hydrated before cement is added or a homogenous and fully hydrated backfill would not be obtained.

A soil-cement-bentonite backfill with a target c/w ratio of 0.15 was selected for use. It was anticipated that the actual c/w ratio would fluctuate during construction, and therefore a midrange value was specified. A well graded, locally sourced sand was used for the soil component. Figure 7 shows the particle distribution curve (PDC) of the sand used for construction along with the upper and lower bound PDC specified. The target fines content specified was between 20% and 40%, with the intent to have the fines content help lower permeability. However, the sand supplied during construction typically contained 15% to 25% fines (<80 µm diameter) due to variations in the sand at the borrow source. The minimum fines content specified was adjusted to 15% after consideration, with laboratory tests confirming the permeability requirements were met. The sand provided bulk to the mix, reducing the quantity of cement and bentonite needed. It also reduced permeability by creating a more tight structure, with less pore space compared to the cement-bentonite mix.

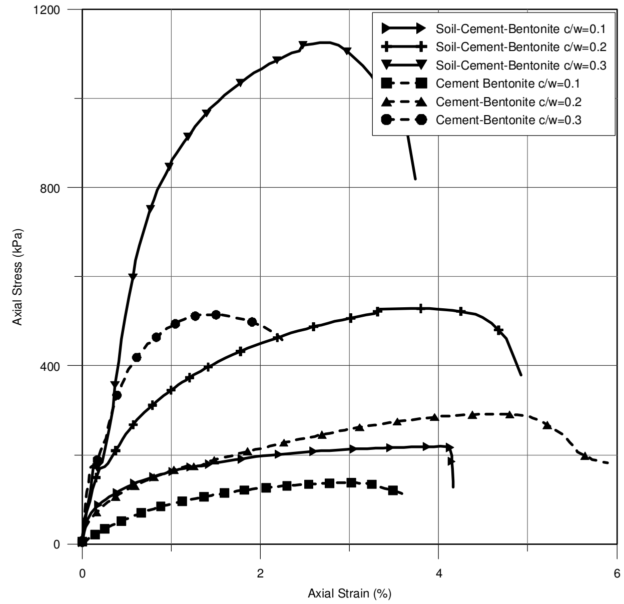

Figure 1. Stress versus Axial Strain Measurements For Various Backfill Mixtures (UCS test).

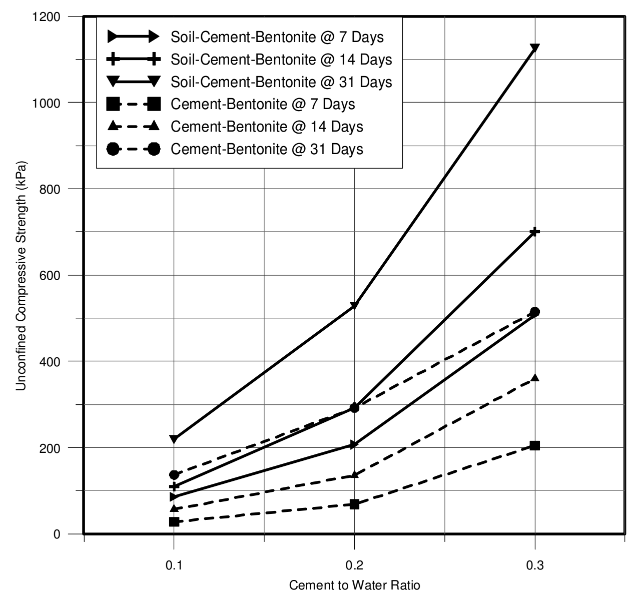

Figure 2. UCS versus C/W Ratio at Various Sample Curing Times.

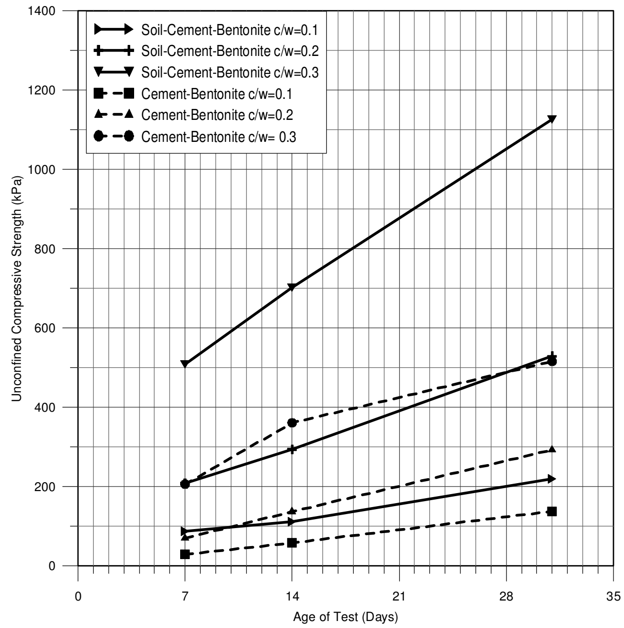

Figure 3. UCS Tests versus Sample Curing Times For Various C/W Ratios.

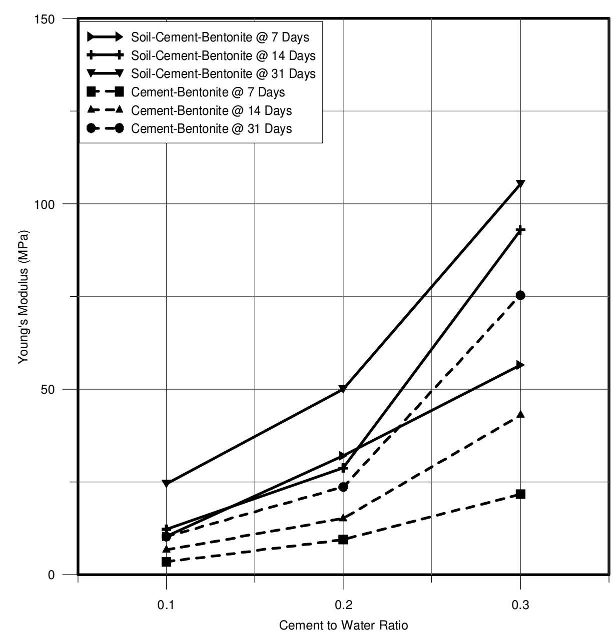

Figure 4. Measured Young's Modulus versus C/W Ratio for Various Sample Curing Times.

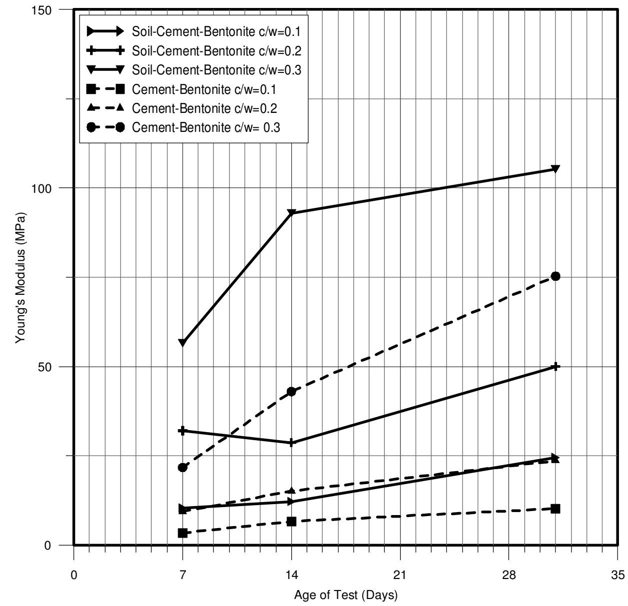

Figure 5. Measured Young's Modulus versus Sample Curing Time for Various C/W Ratios.

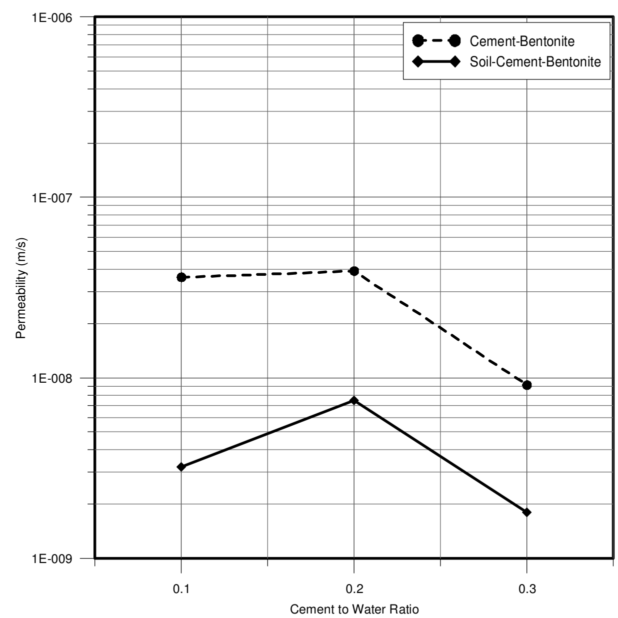

Figure 6. Measured Permeability for Various C/W Ratios.

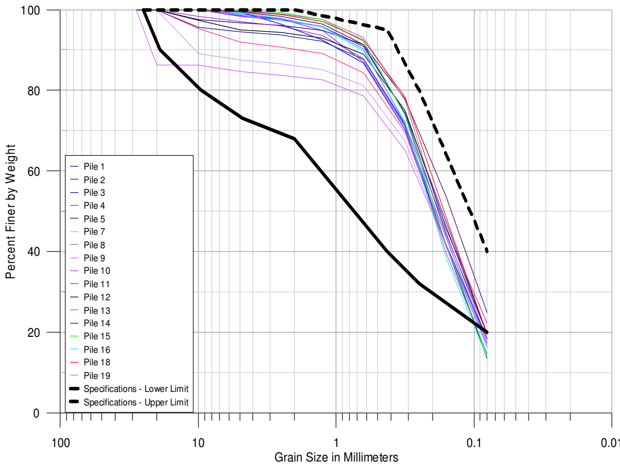

Figure 7. Particle Distribution Curve of Sand

4 CONSTRUCTION OF CUT OFF WALL

4.1 General

The slurry wall was constructed in two stages. The first stage consisted of excavating the entire trench, with simultaneous placement of a hydrated bentonite-water slurry in the trench to provide wall stability. The second stage consisted of backfilling the trench with the soil-cement-bentonite backfill. The intent of "de-coupling" the excavation and backfill was to make the construction process less susceptible to delays caused by cold weather and to avoid problems related to hardening of the backfill.

Two 60 m^3 water tanks, a boiler system and one high shear mixing tank able to mix a volume of 45 m^3 were used to batch the slurry. The water was maintained at a temperature of 40^{o}C during batching. A pond with 600 m^3 capacity was built near the cut off wall to store slurry for hydration. A pump moved hydrated slurry from the pond to the trench, and to the backfill mixture. The pump had an in-line flow meter which recorded the quantity of slurry pumped into the backfill mix.

To provide a level area for the excavation and backfilling, a work pad approximately 30 m wide was constructed from common fill. A clay cap was eventually built at the top of the completed slurry wall, and tied in with the existing fill.

A Long Stick hydraulic excavator, which had a maximum reach of 14 m, was used to excavate the trench. This excavator had the capability of reaching long distances facilitating cleaning the trench bottom. Backfill mixing was carried out with two hydraulic excavators – one excavator had a clean out bucket and the other had an "Allu" bucket attachment. The "Allu" bucket ran through the sand stockpiles prior to mixing slurry and cement, which removed large rocks and broke down lumps of soil. It was then used to thoroughly mix the dry cement into the sand. Slurry was added (monitored with the flow meter) to the sand-cement mixture until the required c/w of 0.15 was reached. The excavators tracked back and forth through the backfill, mixing the slurry into the sand-cement mixture. The backfill was then placed into the trench, at the top of the previously placed backfill, allowing it to flow down at its natural angle of repose (approx. 3.5H:1V), being careful to not encapsulate any slurry in the trench.

Figures 8 and 9 show a typical cross and longitudinal section of the slurry trench, respectively.

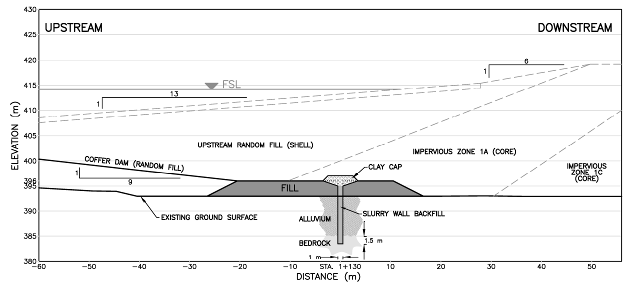

Figure 8. Typical Cross Section of Cut Off Wall.

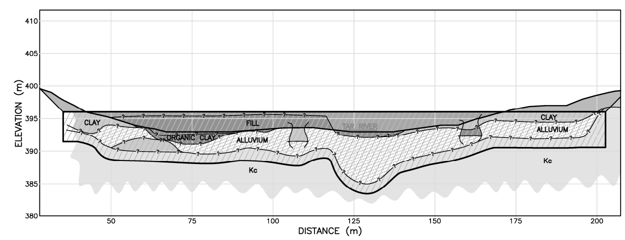

Figure 9. Longitudinal Stratigraphic Section of Cut Off Wall.

4.2 Cold Weather Construction

Due to tight schedule constraints, construction of the cut off wall took place at the tail end of winter, which meant variable weather conditions. Ambient temperatures ranged from -34^{o}C to +11^{o}C during the construction period, with a severe snow storm occurring right at the beginning of the project.

Since the slurry trench technique requires the use of water, and the backfill contained cement (which cannot freeze for proper hydration), the contractor had to supply the necessary equipment and materials to prevent the water, slurry (hydrating and in-trench), and backfill from freezing. As described above, a boiler system and mixing tank, typically used in the oil field drilling industry, were used to keep the mixing water above 40^{o}C. The slurry in the hydrating ponds and in-trench could be re-circulated and reheated in the mixing tank through use of steam pipes if necessary. The hydrating ponds were covered with plastic tarps to help stop the loss of heat.

At the end of wall construction, a temporary fill (several meters thick) was placed over its top to protect the backfill from freezing and dehydration.

The methods described above were effective in protecting all materials during and after construction, and were integral in the successful completion of the cut off wall. Figure 10 presents the batch plant set-up and construction of the cut off wall.

Figure 10. **Above**: Batch Plant, **Lower**: Slurry Wall Construction.

4.3 Quality Assurance/Control

A quality assurance/control program was implemented to confirm that the design requirements were met during construction. Backfill samples were collected at approximately every 15 m interval along the trench wall for confirmatory UCS and permeability testing. A summary of the results are provided on Figures 11 to 14. The results indicate that the as-built permeability is well below the target value of 1×10^{-8} m/s. Also, the UCS strength results are typically within the design strength requirements. It can be seen that there is a wide range in UCS values and stiffnesses. This is believed to be caused by difficulties in controlling the loss of slurry during the mixing process, which varied the c/w ratio.

The slurry was also tested for density and Marsh funnel viscosity conforming to API standards (*API* 1980). The specific gravity of the slurry was maintained at least 0.3 g/cm^3 less than that of the backfill, ensuring the backfill fully displaced the slurry.

The depth of the wall was measured every 5 m to confirm it was keyed into the bedrock as specified. The owner surveyed the top of the cut off wall to confirm elevation and location subsequent to the backfill setting, and before construction of the clay cap.

During construction of the clay cap, a deficiency was found in the backfill. The last 10 m of backfill material did not meet the specified strength and stiffness requirements. The deficiency at first appeared to be from a lack of cement, however under further investigation the cause was unclear. Organics were noted at this location during excavation of the trench, buried within the colluvium. The presence of organics (tannic acids) could potentially retard the hydration process of the cement (PCA 2002).

The cut off wall was repaired by excavating another slurry trench upstream of the defective portion of the wall, overlapping and keying into the competent portion of the wall.

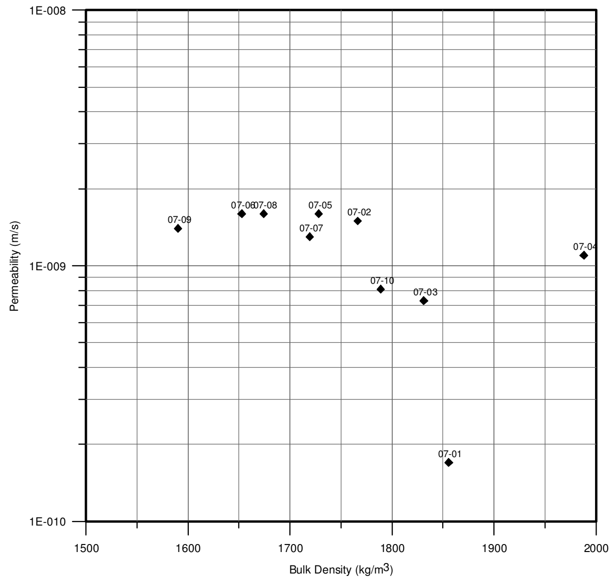

Figure 11. As-Built Permeability Results of Backfill Samples Collected During Construction.

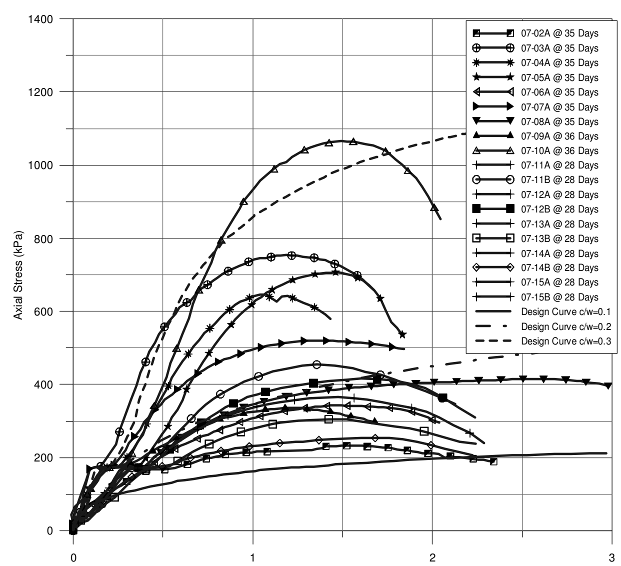

Figure 12 As-Built Strength versus Axial Strain of Backfill Samples Collected During Construction (UCS Test).

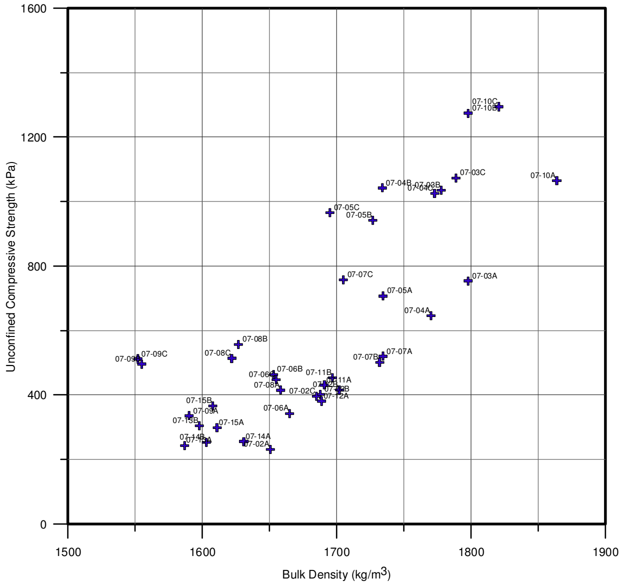

Figure 13. As-Built UCS Tests versus Bulk Density.

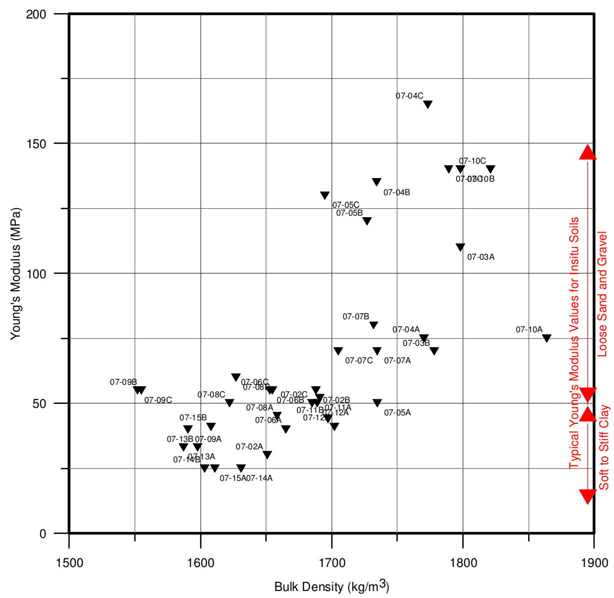

Figure 14. As-Built Young's Modulus of Backfill Samples Collected during Construction.

5 PERFORMANCE OF CUT OFF WALL

The performance of the cut off wall was assessed by the measurement of pore pressures using Vibrating Wire Piezometers installed in the alluvium deposits both upstream and downstream of the cut off wall. Figure 15 illustrates pore pressures along a longitudinal section through the dam and the wall. It can be seen that the cut off wall is effective in maintaining the high hydraulic gradients across the cut off wall caused by the reservoir impoundment.

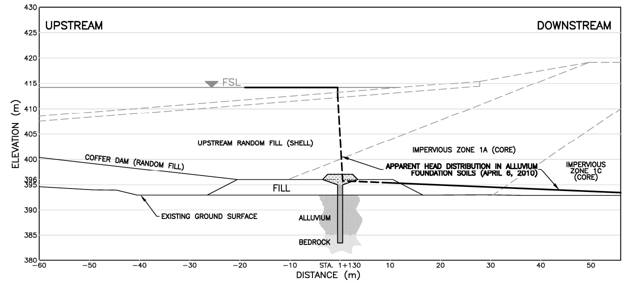

Figure 15. Hydraulic Head Elevation in Alluvium Across Cut Off Wall.

6 CONCLUSION

The design and construction of a soil-cement-bentonite seepage cut off wall for the Horizon Dam was completed successfully. Unique design issues governed the selection of a backfill mix that required extensive testing and quality control to obtain a suitable product. Due to a tight schedule, the cut off wall was constructed under inclement weather conditions which required special equipment to prevent the materials and cut off wall from freezing. Although strict quality control/assurance measures were implemented, one defect in the cut off wall occurred, which required mitigation to provide a product that met the design intent.

ACKNOWLEDGEMENTS

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