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Case Study: Construction and *In-Situ* Hydraulic Conductivity Evaluation of a Deep Soil-Cement-Bentonite Cutoff Wall

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ABSTRACT

This paper presents a case study of a deep soil-cement-bentonite (SCB) slurry trench cutoff wall constructed outside of Smithland, KY in 2010. Installed to a maximum depth of 56 m, this cutoff wall is the deepest known seepage barrier installed using continuous trenching. The wall was installed around the perimeter of a deep excavation to reduce long-term dewatering costs associated with construction of a hydroelectric power plant adjacent to the Ohio River. After wall construction, a dewatering system was installed inside the area enclosed by the wall to facilitate the deep excavation. Pre-construction design and construction details are presented along with the results of a post-construction assessment of the hydraulic conductivity (*k*) of the wall. Steady state groundwater flow measurements from the dewatering system coupled with information on the wall thickness and water levels inside and outside of the wall were used to obtain a large scale estimate of the *in-situ k* of the wall. The *in-situ k* was compared to laboratory *k* values measured for specimens prepared from grab samples of the as-mixed SCB backfill. Comparisons also were made to the target (design) *k* and the expected field mixed backfill *k* established during a preconstruction bench-scale study. The comparisons revealed that the *in-situ k* is approximately one order of magnitude less than the design *k* and approximately equal to the average laboratory *k* measured from grab samples and the expected *k* from the results of the bench scale study.

INTRODUCTION

Slurry trench installation methods are widely employed for the installation of vertical groundwater cutoff systems. The methods and procedures for the proper installation of cutoff walls installed using the slurry trench cutoff wall installation method have been the topic of numerous previous publications (D’Appolonia and Ryan 1979, Millet and Perez 1981, Millet et al. 1992, Evans 1993, Ryan and Day 2003). Walls installed in this way are commonly identified by the backfill type, i.e. the material that makes up the final wall. The three most common slurry trench cutoff wall types are soil-bentonite (SB), cement-bentonite (CB), and soil-cement-bentonite (SCB). SB walls are the most cost effective and therefore most common of the three, but both CB and SCB walls have found growing acceptance and application in the US over the last two decades. Over the last 30 years, cutoff walls installed using slurry trenching methods have consistently proven to be a cost effective means for groundwater control and contaminant

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containment (Evans et al. 1985, Barvenik and Ayres 1987, Day 1994). Innovative construction methods have seen their application range grow to a large variety of construction sites with vastly different constraints and subsurface conditions. Slurry trench installation methods were used in 2010 to construct a deep SCB wall near Smithland, KY as part of a construction dewatering system installation. The wall was designed as an integral part of an excavation water management system for the construction of a hydroelectric power plant along the Ohio River. The wall was and still is, to the authors' knowledge, the deepest of its kind. Dewatering data collected post wall installation has provided a rare opportunity to approximate the field scale performance of this wall. This paper presents the results of a preconstruction bench scale study, provides a brief description of the construction methods utilized on this project, and presents calculations of the wall's hydraulic conductivity based on geometry, material properties, and measured flow. The findings reveal the wall, as constructed, has a system hydraulic conductivity (*k*) approximately equal to that measured from tests on wet grab samples and from the results of preconstruction bench scale studies.

SITE SOIL DESCRIPTION

The project site is located just north of Smithland, KY immediately adjacent to the Ohio River. The site's close proximity to the Ohio River dominates the near surface soil stratigraphy which is consistent with alternating river deposits of varying classification and grain size. The project designers assumed that the soils from the ground surface down to approximately 47 m (155 ft) were highly permeable and these materials were assigned a horizontal hydraulic conductivity of $1x10^{-1}$ cm/s. The macro permeability of these "near" surface overburden soils is dominated by the presence of cemented sand and gravel layers. Limestone bedrock underlies the overburden soils. This bedrock is known to be karstic in nature. The designers assigned the rock layer from beneath the overburden soils down to 100 m (328 ft) below ground surface (BGS) a design hydraulic conductivity of $3x10^{-4}$ cm/s. A second bedrock layer underlying the limestone was assigned a design hydraulic conductivity of $1x10^{-5}$ cm/s. The authors did not consider flow through this second bedrock layer or any deeper layers in their calculations as the overburden soils and upper limestone bedrock layer control the flow for this project.

DESIGN

The circumferential cutoff wall was designed as an integral part of the construction dewatering system for a deep excavation in highly permeable soils immediately adjacent to the Ohio River (see Fig. 1). The deep excavation was for the construction of a hydroelectric power plant.

A SCB backfill, created by mixing the site soils with a bentonite-water slurry and Portland cement-water grout, was chosen for the barrier wall. The SCB backfill was chosen over SB or CB for its combination of moderate strength and low permeability.

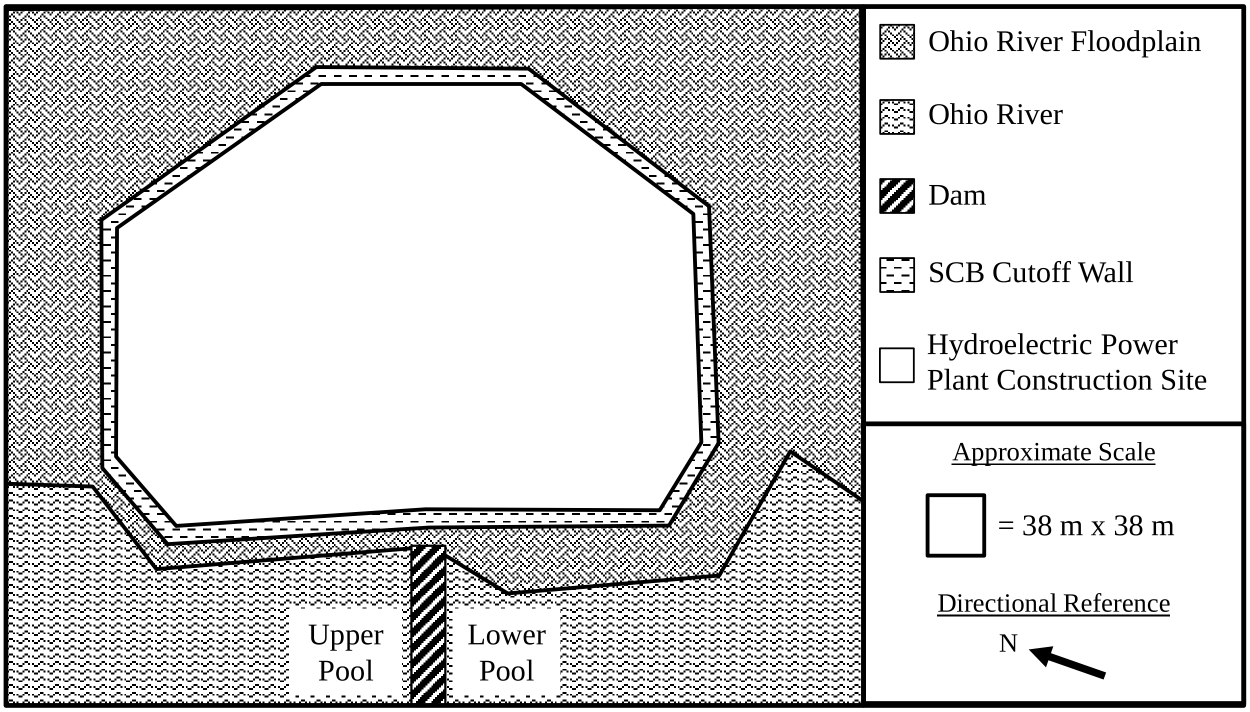

Fig. 1. Plan View of Smithland Cutoff Wall (SCB Cutoff Wall width not to scale)

Given the uneven nature of the bedrock surface, the karstic nature of the underlying bedrock, and the chosen construction method, 100% contact between the bedrock and the cutoff wall was not considered feasible or necessary in the design. As such, the wall was designed to be a continuous 0.9 m (3 ft) wide, $1x10^{-6}$ cm/s barrier wall in contact with the underlying bedrock along greater than 90% of its length and within 3 m (10 ft) of bedrock over the remainder of its length, i.e. less than 10% of the total length. The dewatering system was then designed to account for the resulting "window" beneath the wall bottom and through the bedrock. The design assumption, and construction requirement, therefore assumed windows would have maximum dimensions of 10% of the wall length long and 3 m (10 ft) tall. To facilitate future construction, a moderate strength target of 200 kPa (30 psi) was also included.

PRECONSTRUCTION BENCH SCALE STUDY

In order to assess the feasibility of creating a soil, cement, and bentonite mixture that would meet the project objectives, a preconstruction bench scale study was conducted. Two site soil composites, Composite 1 and Composite 2, were created using soils collected in five borings along the cutoff wall alignment. Although both composites were similar in nature, the soils used to create Composite 1 were chosen to create a finer composite whereas the soils used to create Composite 2 were chosen to create a coarser composite. The choice to create two composites with visibly different properties stemmed from the need to determine an average and maximum expected permeability of the field mixed backfill. A summary of the results of the soil index testing completed on Composites 1 and 2 is presented on Table 1.

Table 1. Preconstruction Bench Scale Soil Index Test Results

Composite ID	Lab Description	Moisture content (%)	Fines Content (%)
Composite 1	Silty Sand, Non-Plastic Fines	16.0	29.5
Composite 2	Silty Sand, Non-Plastic Fines	11.5	19.0

Based on a comparison of the site borings to the results of the soil index testing conducted on the site soil composites, Composite 1 was generally more representative of the soils close to the River and Composite 2 was generally more representative of the soils further away from the River.

Two Portland cement addition rates were tested on the two site soil composites for a total of four SCB mixes. The composition of the four SCB mixes is summarized on Table 2.

Table 2. SCB Sample Composition Summary

Mix ID	Soil Composite	Bentonite (%)	Cement (%)
S-1	Composite 1	0.9	5
S-2	Composite 1	0.8	7
S-3	Composite 2	0.6	5
S-4	Composite 2	0.5	7

The SCB backfill mixes for the preconstruction study were mixed according to the following general procedure:

1. Create a 6% bentonite to water (by weight) slurry and set it aside to hydrate.
2. Weigh the soil needed for each mix, pass it through a 12 mm (0.5”) sieve to remove large particles or clods, and set it aside for use in Step 5.
3. Calculate the cement needed for each mix using the dosage rates in Table 2 applied to the soil quantity from Step 2.
4. Mix the cement from Step 3 with one part water for every one part cement to create a one to one (by weight) cement to water grout.
5. Add the cement-water grout to and mix it with the site soils from Step 2.
6. Condition the soil-grout mixture using the slurry from Step 1 to achieve a SCB backfill with a workable slump in the range of 75 – 150 mm (3” – 6”).
7. Continue to mix the SCB backfill until visually homogeneous.
8. Cast the SCB mixture in plastic cylinders (general casting procedures presented later).
9. Allow the cylindrical SCB backfill specimens to cure prior to lab testing.

After 14 days of curing, unconfined compression and *k* testing was performed. Time constraints prevented *k* testing after 28 days of curing. The results of the unconfined compression and *k* testing performed after 14 days are presented on Table 3.

Table 3. Hydraulic Conductivity and UCS of Preconstruction Bench Scale Study Mixes

	14 day UCS	14 day Hydraulic Conductivity, *k*
Units	kPa [psi]	cm/s
S-1	172 [25]	4.6×10^{-7}
S-2	193 [28]	4.7×10^{-7}
S-3	400 [58]	6.7×10^{-7}
S-4	470 [71]	1.2×10^{-6}

Most of the results of the bench scale study were consistent with that expected from previous studies; the mixes created from Composite 1 exhibited a lower *k*, the mixes created from Composite 2 exhibited a higher strength, and the higher cement addition rates produced higher strength results compared to the lower cement addition rates for each soil composite. The only result that did not entirely fit with the others was the *k* of mix S-4 which was prepared at the high cement content and mixed with a composite sample representing the lowed fines content. The higher cement addition rate combined with the lower fines content may have resulted in a sample structure of the mix to produce the highest measured value of *k*. Alternatively, it's possible that this result is due to an anomalous specimen. In any case, the 14 day results showed that the design objectives could be met at 28 days with a suitable factor of safety using a mixture consisting of site soils, 5% cement added by total soil weight in a one to one cement-water grout, and enough 6% bentonite slurry to achieve a workable slump. Based on the authors' past experience, SCB backfill strength can increase by approximately 50% and the *k* can decrease by approximately 100% from 14 to 28 days. Table 4 presents expected 28 day results for the recommended mix determined using past experience applied to the 14 day results.

Table 4. Expected Hydraulic Conductivity and UCS of Recommended Mix

	28 day UCS	28 day Hydraulic Conductivity, *k*
Units	kPa [psi]	cm/s
Composite 1	240 [35]	3×10^{-7}
Composite 2	600 [85]	4×10^{-7}

CONSTRUCTION

Industry standard slurry trench installation procedures were utilized for the wall installation. The upper portion of the trench was excavated using a 113 tonne (125 ton) excavator fitted with a specialty boom and "long" stick. This excavator combination was used down to 27 m (90 ft) below ground surface (BGS). Excavation deeper than 27 m (90 ft) BGS was completed using crane mounted hydraulic and mechanical clamshell buckets digging primary and secondary panels. The average wall depth was 47 m (155 ft) and the maximum wall depth was 56 m (185 ft). Fig. 2 shows a photograph of the long stick excavator and clamshells excavating the cutoff wall.

Fig. 2. Photograph of Clamshells (foreground) and Long Stick Excavator (background) excavating the Smithland Cutoff Wall

Initial SCB backfill placement was completed using a custom built tremie pipe. After the "head" of the backfill reached the surface, the SCB backfill was pushed into the trench using a small hydraulic excavator. All of the backfill was remotely mixed on-site at a central location. Dump trucks were used to haul trench spoils from the trench to the mixing location and the mixed SCB backfill from the mixing location to the trench.

Cutoff walls constructed using the SCB slurry trench construction methods are sometimes criticized because of the potential for coarse particle settling on the backfill slope and therefore the potential for the creation of higher permeability lenses. Evidence from the literature on a cutoff wall constructed using similar construction techniques indicates that the permeability of any leftover coarse particle lenses may be nearly as low as that of the backfill, probably due to the *in-situ* mixing of the sediment and the slurry (Evans et al. 2004). For this project, given the sandy nature of the overburden soils, backfill slope profiling and cleaning was of critical importance to identify and remedy anomalous areas. The crew on this project profiled 4 times per day (twice per shift) and cleaned the backfill slope from head to toe at least once per day to remove the upper portion of the backfill in areas where the slope profile indicated that there was a chance that coarse particle settling or trench sidewall spalling had occurred.

Based on the construction record, the authors believe that most of the wall panels were installed down to bedrock, but that gaps may have been left between the cutoff wall bottom and limestone bedrock associated with the horizontal clamshell bucket not being able to seat perfectly across a sloped and irregular bedrock interface as illustrated on Fig. 3.

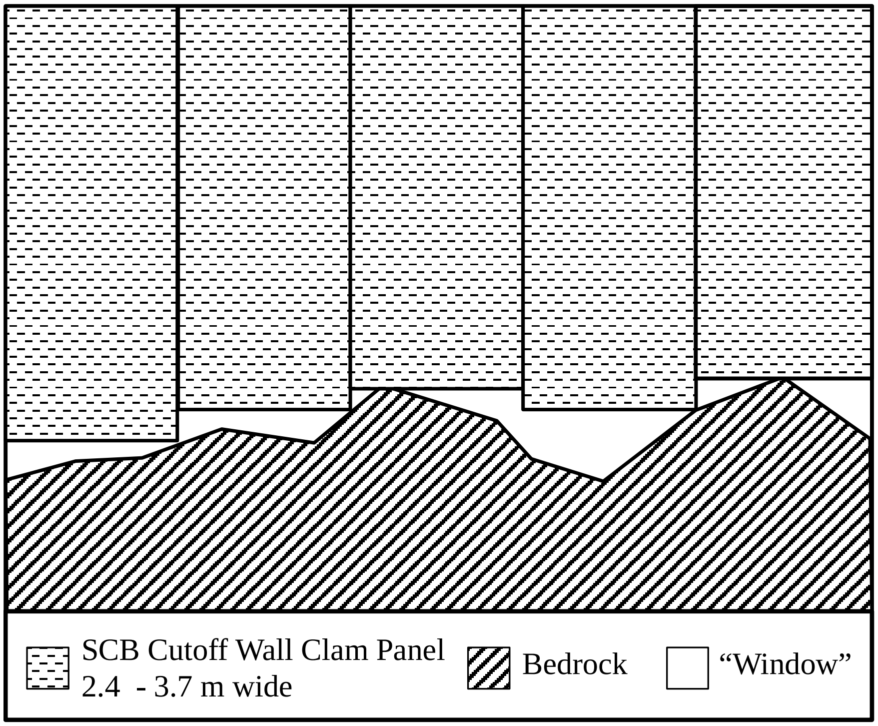

Fig. 3. Schematic of Potential “Windows” Beneath the Cutoff Wall (not to scale)

Following the cutoff wall installation, a pumping system was installed inside the cutoff wall to dewater the interior of the excavation. In total, 54 wells were installed in two stages, one near the top of the excavation and another lower down in the excavation.

LABORATORY TESTING ON WET GRAB SAMPLES OF SCB BACKFILL

The most widely accepted and commonly used approach to determine whether or not a vertical cutoff wall has achieved the design permeability and strength objectives is to conduct laboratory tests on cylindrical samples cast from wet “grab” samples of the backfill. For this project, SCB backfill samples were taken immediately after the backfill was mixed and prior to placement in the trench at a frequency of 1 sample for every 760 m^3 (1000 CY) of backfill placed. The wet backfill was then cast in 75 mm diameter and 150 mm long plastic cylinders using methods that minimized the entrapment of air. The general procedure for casting wet SCB samples was:

1. Fill 1/3 of the cylinder with wet backfill
2. Rod the wet backfill in the cylinder 20 – 25 times using a 12 mm rod
3. Tap the 1/3 full cylinder against a hard surface 20 – 25 times
4. Fill the cylinder to 2/3 full

5. Repeat rodding and tapping from Steps 2 and 3
6. Fill the remaining 1/3
7. Repeat rodding and tapping from Steps 2 and 3
8. Screed the surface of the cylinder using a trowel or other sharp edge

Once cast, the cylinders were stored on site using efforts to control the moisture and temperature environment, i.e. the samples were kept in an insulated cooler with free water and kept out of direct sunlight. After 3 to 5 days of field curing, the cylinders were transported to a laboratory for additional curing followed by permeability and unconfined compressive strength (UCS) testing at a minimum frequency of one test for every 1,520 m^3 (2000 CY) of backfill placed. Consistent with conventional practice, permeability and UCS tests were conducted after 7 or 14 and 28 days of curing with the 7 or 14 day results used as preliminary indicators and the 28 day results used to determine acceptance.

Thirty nine grab sample locations were tested for the Smithland cutoff wall. The average, maximum, and minimum UCS and *k* results from tests conducted on 28 day old specimens are presented on Table 5.

Table 5. Avg., Max., and Min. Hydraulic Conductivity and UCS of Grab Samples

	28 day UCS	28 day Hydraulic Conductivity, *k*
Units	kPa [psi]	cm/s
Average	365 [53]	2.2×10^{-7}
Maximum	738 [107]	8.7×10^{-7}
Minimum	186 [27]	7.8×10^{-8}

The results of the *k* and UCS testing on grab samples were consistent with the results of pre-construction bench scale testing using site soils which demonstrated backfill mixtures performing better than the design objectives of 207 kPa (30 psi) and 1×10^{-6} cm/s.

EVALUATION OF SYSTEM PERMEABILITY

Dewatering of a "bathtub" requires removal of pore water as the soil transitions from saturated to unsaturated as well as removal of infiltrating water from groundwater and precipitation. As a result, initial pumping rates are higher than steady state pumping rates which only need to remove infiltrating groundwater and precipitation. As of the Spring of 2013, 32 of the 54 installed wells were being continuously operated and removing 757 l/s (12,000 gpm) (Jay Fairbanks / Ed Bach, personal communication, 2010 – 2013). This pumping rate represents the steady state rate over approximately three years of continuous operation.

An estimate of the *in-situ* *k* of the cutoff wall can be calculated assuming steady flow and using Darcy's law as follows:

$$q = kiA \qquad (1)$$

Where q = flow rate (l/s), k = the coefficient of hydraulic conductivity (cm/s), i = hydraulic gradient (m/m), and A = cross-sectional area perpendicular to the direction of flow (cm^2).

Replacing the conventional parameters in Eq. 1 with site-specific parameters (see Table 6) results in Eq. 2:

$$q = k\left(\frac{(WL_o - WL_i)}{W}\right)(A_w) \qquad (2)$$

The site specific parameters presented in Eq. 2 are defined in Table 6 along with a presentation of the average values of these parameters and other pertinent information about the Smithland cutoff wall including the wall length, average wall height, water level inside of the wall, water level outside of the wall, and the average pump rate.

Table 6. Observed and Calculated Average Parameters for the Smithland Cutoff Wall

Parameter	*Range*
Wall Width, W	0.91 m
Wall Length, L	1161.9 m
El. of "Rock"	57.5 m
Average Wall Height, H	46.9 m
Water Level Outside (elevation), WL_o	96.0 m
Water Level Inside (elevation at steady state pumping), WL_i	56.1 m
Wet Height, $H_w = WL_o$ – El. of "Rock"	38.5 m
Pumping Rate, q	$7.6x10^5$ cm^3 / s (avg)
Wetted Area, $A_w = L \times H_w$	$4.5x10^8$ cm^2

Although the flow rate in Eq. 2 is a combination of infiltrating groundwater and precipitation, the precipitation component was ignored because its contribution was determined to be negligible (less than 0.5%) in comparison to the steady pumping rate.

To obtain an estimate of the upper limit of the wall k, Case 1 in Table 7, all flow entering the system was assumed to be entering through the wall and not under the wall. This assumption is very conservative (unrealistic) given the karstic nature of the bedrock underlying this site and the understanding that high permeability "windows" are inevitable beneath the wall. The maximum *in*-situ k for the barrier of $3.8x10^{-5}$ cm/s was calculated by solving Eq. 2 for k using the parameters presented in Table 6 and using the worst-case scenario that assumes all flow is through the wall.

Given the long history of successful cutoff wall construction and the designer's recognition that it would be difficult or impossible to seat the wall directly on the bedrock, it's reasonable to assume that the infiltrating groundwater is actually a combination of flow through the wall, flow through overburden soil windows beneath the wall, and flow beneath the wall through the bedrock.

Using the design *k* values for the overburden soils and limestone bedrock presented in the site soil description and assuming the wall is in contact with the bedrock over greater than 90% of the wall length and 3 m (10 ft) above the bedrock over the remaining length, i.e. the minimum requirements for construction, two flow nets were drawn as shown in Fig. 4. In order to simplify the flow net construction and because it is believed to represent less than 0.5% of the steady pumping rate, flow through the wall was neglected in the construction of these flow nets.

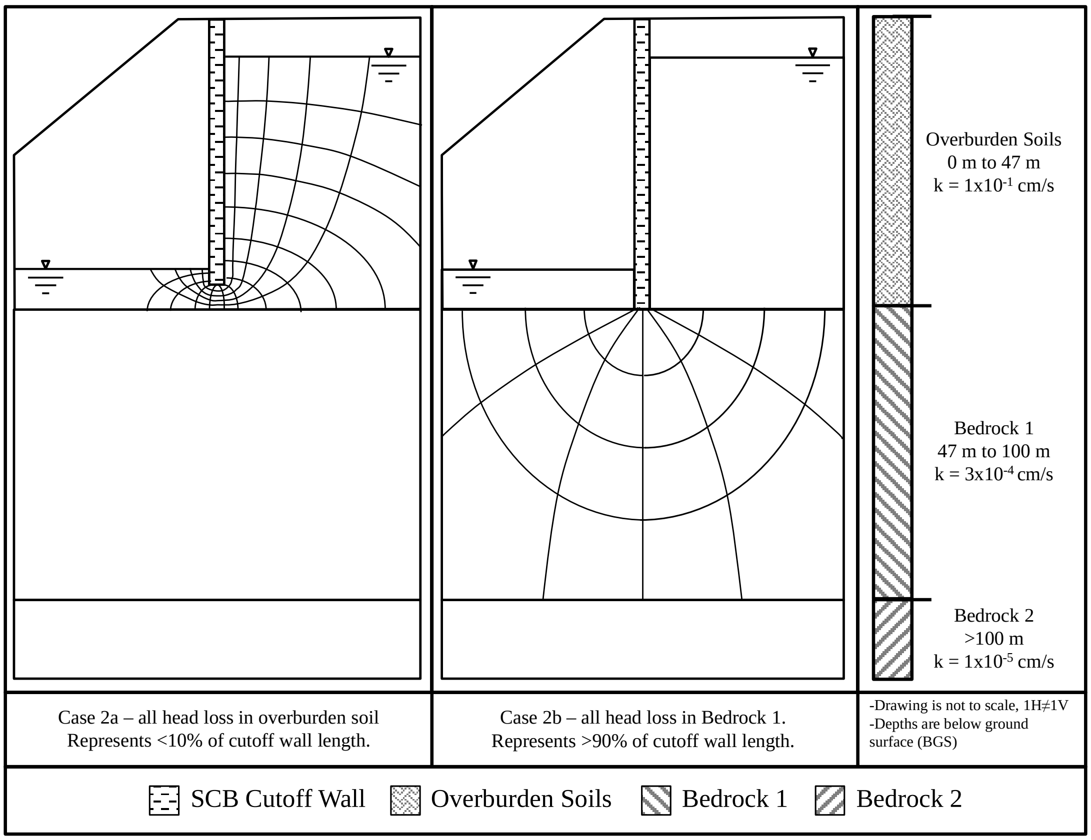

Fig. 4. Conceptual Flow Nets for Flow through Bedrock and Overburden Soil "Windows"

To further bound the problem, the upper limit of flow beneath the wall was calculated. Using the graphical representations of flow in Fig. 4, the site specific information presented in Table 6, and the assumption that the wall is in contact with the bedrock over the minimum specified length, 90%, to calculate the flow through the overburden soil "window" and underlying bedrock yields a flow that is greater than the measured steady state flow under the wall with approximately 95% of this calculated total flow going through the overburden soil "window" and 5% travelling through the limestone bedrock. These calculations show that the actual window area must but less than the maximum allowed by design and that the predominant flow path is through windows beneath the wall.

To further refine the analysis, it is recognized that the cutoff wall is not totally impermeable and it is impossible for the computed flow beneath the wall to be greater than or even equal to the steady state flow rate. For this case, a more realistic approach is to assume that the cutoff wall *k* is equal to the measured *k* from the laboratory tests on the grab samples and to use this assumption in Eq. 2 to calculate the flow through the wall. This calculation yields a flow through the wall that is slightly more than 0.5% of the total flow which results in the calculation that the wall is seated on the bedrock along slightly less than 96% of its length. In this case, Case 2 in Table 7, the flow through the underlying bedrock makes up approximately 11.8% and the flow through the soil windows makes up approximately 87.7% of the total flow entering the system. Table 7 shows a summary of the estimated *k* from the two cases presented above.

Table 7. Summary of Estimated Cutoff Wall *k* from Dewatering Data

Case #	Flow through Wall (%)	Flow through Overburden Soil Windows (%)	Flow through Underlying Bedrock (%)	Estimated Wall *k* (cm/s)
1	100	0	0	$4x10^{-5}$
2	0.5	87.7	11.8	$2x10^{-7}$

Based on these analyses, flow through the cutoff wall is probably very small in comparison to the flow beneath the wall and the cutoff wall is seated directly on the bedrock over at least 95% of its length. Although the cross-sectional area of the unimproved soil windows is probably small in comparison to the cross-sectional cutoff wall area, the windows would carry the majority of the flow into the system due to the relatively high permeability of the overburden soils.

CONCLUSIONS

At the time of its installation, the Smithland cutoff wall was the deepest of its kind; a continuous seepage cutoff wall installed using conventional SCB slurry trench excavation and backfill methods. Over its first three years of performance, this wall has exceeded design expectations. While concerns of entrapped sediment have been noted for open trench cutoff walls, performance of this wall supports the assertion that proper profiling and sediment cleaning can be used to identify and remedy potential problem areas prior to backfill placement. This case study is a documented example of a successful SCB cutoff wall that resulted from proper construction and monitoring procedures.

The industry standard manner of measuring the properties of SCB cutoff walls is to collect grab samples of the backfill, cast the grab samples in plastic molds, cure the molded specimens for 7 to 28 days, and test the strength and *k* of the cured specimens in a laboratory. The casting and curing procedures used to prepare the backfill specimens can impact the measured properties, but based on past experience, the results of testing conducted on wet grab samples are generally representative of the *in-situ* conditions.

This paper illustrates a typical problem in assessing the *in situ* hydraulic conductivity of vertical barriers. That is, mathematically speaking, there are too many variables to develop a unique solution to estimate the *in-situ k* of the wall. Typically, and in this case, there is one measured value of flow and two sources of the flow (through and beneath the wall). For this project, the authors' infer that the *in-situ k* is less than the target *k* and is actually probably closer to the measured *k* of the wet grab samples. Based on the authors' calculations, the cutoff wall *in-situ* system *k* is probably one order of magnitude less than the design *k* of $1x10^{-6}$ cm/s, making the wall 1,000 times less permeable than the underlying bedrock and 30,000 times less permeable than the overburden soils. In all likelihood, more than 99% of the flow going into the excavation is under the wall either through "windows" between the wall bottom and bedrock or through the underlying bedrock.

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