Final Draft:
Full text available at: http://ascelibrary.org/doi/abs/10.1061/9780784480441.018

Design and Construction of an Experimental Soil-Bentonite Cutoff Wall

Jeffrey C. Evans, Ph.D., P.E., F. ASCE[1] and Daniel G. Ruffing, P.E., M. ASCE[2]

[1]Dept. of Civil & Environmental Eng., Bucknell University, Lewisburg, PA, 17837; e-mail: evans@bucknell.edu
[2]Geo-Solutions, Inc., 1250 Fifth Avenue, New Kensington, PA 15068; e-mail: druffing@geo-solutions.com

ABSTRACT

Soil-bentonite slurry trench cutoff walls are widely used for seepage control, levee repair, and pollutant containment. Their widespread use in these critical applications requires a better understanding of their as-built condition and long-term behavior. The *in situ* hydraulic conductivity of soil-bentonite cutoff walls is stress dependent. Changes in hydraulic conductivity of the wall over time can result from changes in stress due to consolidation and load transfer though shear to the formation along the sidewalls of the trench. This paper describes a soil-bentonite cutoff wall designed, constructed, and instrumented for the principal purpose of research. The cutoff wall instrumentation is designed to monitor the *in situ* conditions in the backfill in three dimensions (transverse, longitudinal and vertical), vertical and lateral deformations, and pore water pressures. All data is being collected as a function of time and location within the wall.

INTRODUCTION

Vertical barriers (i.e. cutoff walls) have been employed for more than 40 years to control groundwater flow and subsurface contaminant transport. In the US, the most common type of vertical barrier is the soil-bentonite (SB) slurry trench cutoff wall that takes its name from the nature of the final barrier materials (SB) and the method of construction (slurry trench). The history, uses, and methods of construction of SB walls are described in great detail in the literature (e.g. Millet and Perez 1981, Evans 1993, Ryan and Day 2003). The purpose of this paper is to 1) describe gaps in the collective knowledge of SB wall performance 2) present an overview of a research program in progress to fill these gaps and 3) show some preliminary results from the research project. The research project is comprehensive and ongoing so key findings will be published as available.

Soil-bentonite cutoff walls are widely used for long-term applications, such as levee repair and geoenvironmental containment, in which the wall is expected to perform as a hydraulic barrier for years, if not decades. In these applications, both the short-term (as-built) integrity of the barrier and the potential for changes over time are of critical importance.

Short-term integrity of SB cutoff walls is typically assessed using quality control/quality assurance (QC/QA) testing of field-mixed SB backfill subjected to laboratory tests (e.g., Millet and Perez 1981, Millet et al. 1992). However, the *in situ* hydraulic conductivity, *k*, of an SB cutoff wall depends upon the *in situ* stress distribution in the wall, which typically is not measured. Although a number of studies have been performed (e.g. Evans et al 1995, Filz 1996, Ruffing et al. 2010) to better understand the state-of-stress in SB walls, gaps in the understanding persist. The stress distribution is influenced by arching as a result of friction forces between the backfill and the trench sidewalls (Evans et al. 1985), and the horizontal stress distribution is influenced by lateral squeezing of the backfill by the adjacent, native formation (Filz 1996 and Ruffing et al. 2010). Laboratory *k* values obtained from field-mixed backfill specimens may not be representative of the *in situ* *k* if the applied stress state in the test is not representative of the *in situ* stress state (National Research Council 2007). Moreover, laboratory *k* tests are insufficient for verifying the absence of high-*k* construction defects, which is a very important component of the system to understand because only a few such defects can significantly increase the overall *k* of the barrier (Britton et al. 2004). In this study, laboratory and field methods for evaluating *k* of a pilot-scale SB cutoff wall were compared. Laboratory *k* values obtained from undisturbed and remolded specimens of the field backfill were consistently lower than larger-scale *k* values obtained from *in situ* measurements (piezocone and piezometer) and pumping tests. Regarding long-term integrity, several factors may cause changes in *k* of an SB barrier over time, including deformations, desiccation, freeze-thaw, and chemical incompatibility (National Research Council 2007). However, the significance of these factors on the effectiveness of field-scale SB barriers is largely unknown, as post-construction monitoring of SB walls is rarely performed and typically involves only monitoring of the aquifer down gradient of the wall rather than testing or monitoring of the wall itself.

Uncertainties in the state-of-stress (and thus *k*), time-dependent changes in backfill properties, variability of *k* under field conditions are the drivers behind this study. The authors are aware of several cases in which constructed cutoff walls have failed to provide the required containment due to construction defects or post-construction changes in the wall, as opposed to design deficiencies. However, published case histories of cutoff wall failures and field investigations are scarce, in large part because site owners find long-term monitoring, other than perimeter ground water monitoring, disruptive, invasive, and costly. While there have been a few field studies in which sampling and *in situ* testing of an SB wall have been performed (e.g., Evans and Ryan 2005, Ruffing and Evans 2010), these studies have been limited in scope and duration due to site access limitations and concerns over potential impacts to the wall. For all of the above reasons, a field-scale cutoff wall built for the express purpose of investigation/experimentation, located at a site where unfettered, long-term access is available, is the best way to get answers about the fundamental performance questions posed above.

UNCERTAINTIES

Based on the above introduction, it is clear that uncertainties exist regarding both the as-built and long-term properties of SB cutoff walls, despite the widespread use of these walls for long-term hydraulic containment applications. In particular, the authors note two important subjects:

(1) Limited knowledge of the *in situ* stress distribution within the barrier, as well as how or whether it varies with orientation and depth.
(2) There exists a potential for time-dependent changes in backfill properties (e.g., dry density, water content, saturation, shear strength, and hydraulic conductivity.)

Each of these subjects is addressed separately in the text that follows.

Uncertainty in the Stress. Both the magnitude and variability of *k* of SB backfill are dependent upon effective stress. A lower effective stress tends to result in higher *k* and greater variability in *k* among replicate specimens. Since effective stress varies with depth, *k* will also vary with depth. Despite numerous studies, uncertainty exists regarding the distribution of effective stress with depth. Limited investigations to quantify the effective stress in SB walls indicate that, for shallow depths (less than 2 m), there tends to be a non-linear increase in vertical stress followed by a stress distribution that is essentially constant with depth up to ~9 m (Evans et al. 1995).

Subsequent investigations (Filz et al. 1999, Ruffing et al. 2010) have revealed that the horizontal stress likely increases with increasing depth due to lateral squeezing of the backfill by the adjacent formation.

Research to investigate the *in situ* stress distribution within SB cutoff walls has been limited primarily to theoretical studies (e.g. Evans et al 1985, Filz 1996, Ruffing et al 2010). However, in one study (Evans and Ryan 2005), earth pressure cells were mounted on sheet pile sections and installed in an SB cutoff wall during construction. The total lateral pressure was monitored for a period of 10 days and had not yet stabilized (i.e., was decreasing with time) when the test was terminated. In another study, described in Ruffing and Evans 2010 and subsequent companion papers, the *in situ* stress state was assessed by performing cone penetrometer testing, dilatometer, and vane shear tests in the constructed wall and by installing volumetric water content probes. All of these test results are stress dependent and were thus selected to assess the stress state. This study was limited by the relatively shallow depth of the wall, the known presence of sizable inclusions in the backfill, and because of access restrictions post construction.

Time-Dependent Changes in SB Backfill Properties. The ability of SB cutoff walls to provide satisfactory long term containment performance warrants serious consideration. While *k* measurements at the time of construction may provide a reasonable indication of short-term hydraulic performance, the test results may not be indicative of long-term hydraulic performance. Changes in backfill *k* may occur long after construction due to factors such as cyclic wetting/drying and freezing/thawing, changes in effective stress, deformations, and interaction between the bentonite and chemical constituents in groundwater (Evans 1993, Shackelford 1994, Evans 1995). Little attention has been given to the effect of these factors on SB backfill, and no comprehensive attempts have been made to investigate these factors in field-scale walls.

The influence of wet/dry cycling on backfill *k* is one important consideration that has received little attention. For levees in particular, some portion of the cutoff wall will be above the water table except during periods of flooding. This portion of the wall must be an effective hydraulic barrier during these flooding periods. A few studies have been performed to assess SB backfill performance as a function of wetting/drying. For example, in the study described in Evans (1994) collected backfill samples from a constructed SB wall from depths of approximately 1 m above and below the adjacent water table revealed a substantially greater *k* for the backfill obtained above the water table relative to the backfill collected from below the water table. These results were supported by measured water content profiles in the backfill, which showed that the water content had diminished in the backfill above the water table. More recently, another study investigated the potential for changes in model (lab) SB backfill *k* subjected to wet-dry cycling, as described in Malusis et al. (2011). The two backfills tested in this study exhibited susceptibility to increases in *k* caused by wet-dry cycling. The findings of this study were consistent with those of Evans (1994) and suggest that there is a potential for increases in SB backfill *k* due to wet-dry cycling as may be present in SB barriers located within the zone of a fluctuating groundwater table.

STUDY DETAILS

As described above, additional field research is needed to understand the behavior of SB cutoff walls used in real-world situations. Thus, the authors secured funding from the National Science

Foundation (NSF) to design and construct an experimental SB cutoff wall that will serve as a dedicated field site for research on the short- and long-term integrity of field-scale SB barriers. The two primary goals of this research are:

(1) to investigate the *in situ* state of stress in the wall, with depth and time;
(2) to investigate changes in other *in situ* properties of the wall, including water content, *k*, and shear strength, with special consideration given to differences above and below the water table

The following text describes the experimental cutoff wall site and provides a general overview of the instrumentation installed in the wall. Data collected using the instrumentation described below will be the subject of follow-up companion papers that will be published as the information is generated.

Experimental SB Cutoff Wall Site. The site for the experimental SB cutoff wall is located approximately 3 km east of the Bucknell University campus in Montandon, PA. Furthermore, the subject site is on the property of a commercial sand/gravel quarry operated by Central Builders Supply (CBS). The wall is located on a portion of the property that has been set aside in perpetuity as a buffer zone between the permitted mining area and an adjacent, natural wetland known as the Montandon Marsh. Figure 1a shows the subject site relative to the state of Pennsylvania, Fig. 1b shows the subject site relative to the nearest town / Susquehanna River, and Fig. 1c shows the subject site relative to the active mining operation and protected wetland.

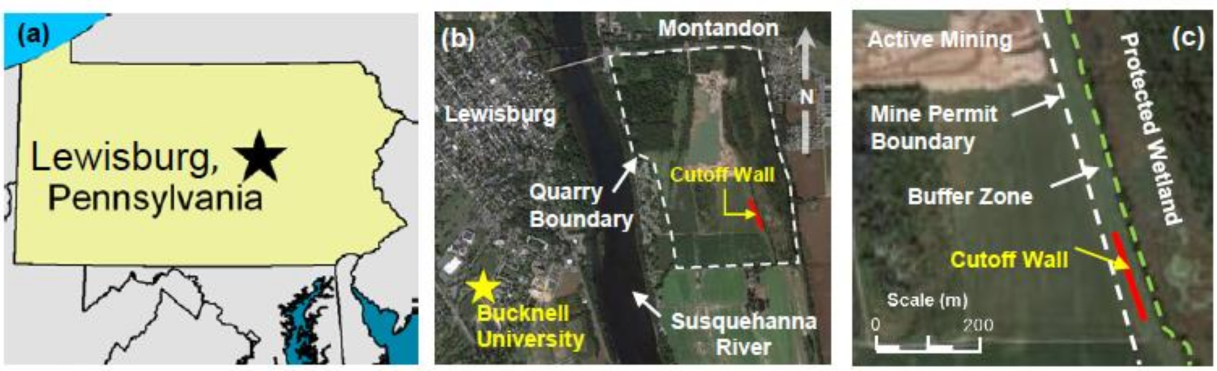

Figure 1. Cutoff wall project location (from Evans et al 2014)

Wall design. At the start of the project, a detailed site characterization program was carried out along the proposed cutoff wall alignment to create a subsurface profile and to obtain samples for laboratory testing needed to design the SB backfill. Borings were completed at 50-m intervals along the alignment using a hollow stem drilling tool mounted on an Acker Soil Scout track-mounted drilling rig. The drilling rig and much of the drill tooling was acquired by Bucknell University in 2008 through a NSF Major Research Instrumentation (MRI) award (Award CMMI-0722584). The surface topography along the alignment was surveyed and used to establish the bottom elevations for the trench. In addition, a baseline electrical resistance geophysical survey was conducted along the alignment to further characterize the subsurface geology, image the depth to bedrock at points between borings, and to check for anomalies that could have impacted wall construction.

The subsurface conditions at the project site generally consist of alluvial and lacustrine deposits within the footprint of the Susquehanna River paleo channel. The local geotechnical and hydrogeologic conditions near the subject site have been well characterized over the years with numerous borings completed by Bucknell's Civil Engineering and Geology departments. Further, the research team conducted eight borings along the alignment, prior to construction. The results of these investigations, generalized on Figure 2, show that the alluvial aquifer is composed primarily of silty and clayey sand containing trace amounts of rounded gravel and cobbles. The aquifer is underlain by lacustrine clay and pinnacled weathered calcareous limestone and shale located generally at a depth of 6 to 12 m below existing ground surface, approximately EL 137 m. The results of the geophysical survey showed a number of limestone pinnacles within the design depth of 7 m. Using the results of the subsurface and geophysical investigations, locations for all monitoring clusters along the wall alignment were selected.

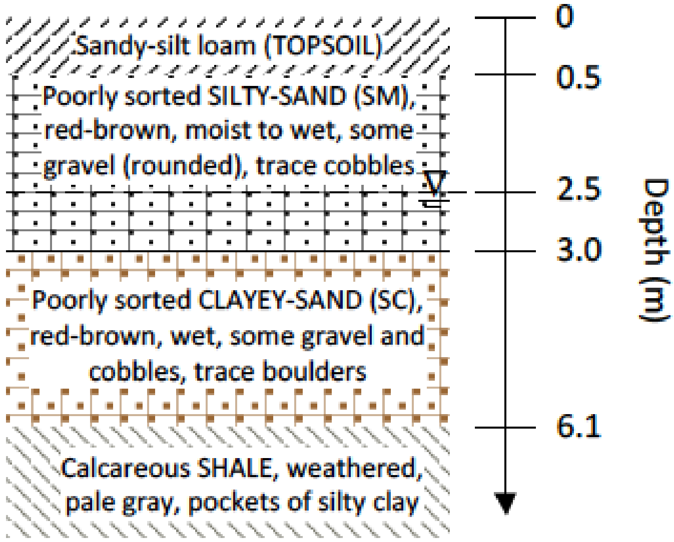

Figure 2. Idealized subsurface profile (from Evans et al. 2014)

Composite samples of material recovered from the borings were used to develop candidate SB backfill mixtures for laboratory testing of slump and *k*. The mixtures were created by blending the composite samples with dry sodium bentonite, as needed for hydraulic performance improvement, and bentonite-water slurry (~5 % sodium bentonite by weight) to achieve a target slump (ASTM C-143) of 125 mm ± 12.5 mm. The targeted slump range was selected to be consistent with typical field specifications for SB backfill (Evans 1993, Ryan and Day 2003). The candidate backfill mixtures were tested in falling head consolidation permeameters so that *k* could be measured as a function of consolidation pressure. Figure 3 shows the results of the *k* testing from which the following general observations are made:

a) Only bentonite via slurry, i.e. no dry bentonite, was needed to produce a *k* between 10^{-6} and 10^{-7} cm/s.
b) Increasing bentonite content generally decreases *k*, independent of stress level
c) All specimens demonstrated a dependency of *k* upon stress level further affirming that if the stress is not known, the true *k* is not known.

Design studies also produced the relationship between stress and coefficient of consolidation, c_v, as shown on Figure 3. Notice that as the bentonite content increases, the sensitivity of c_v to stress decreases. These data were used to predict a time of 16 days to achieve 90% consolidation for the 0.9 m width trench.

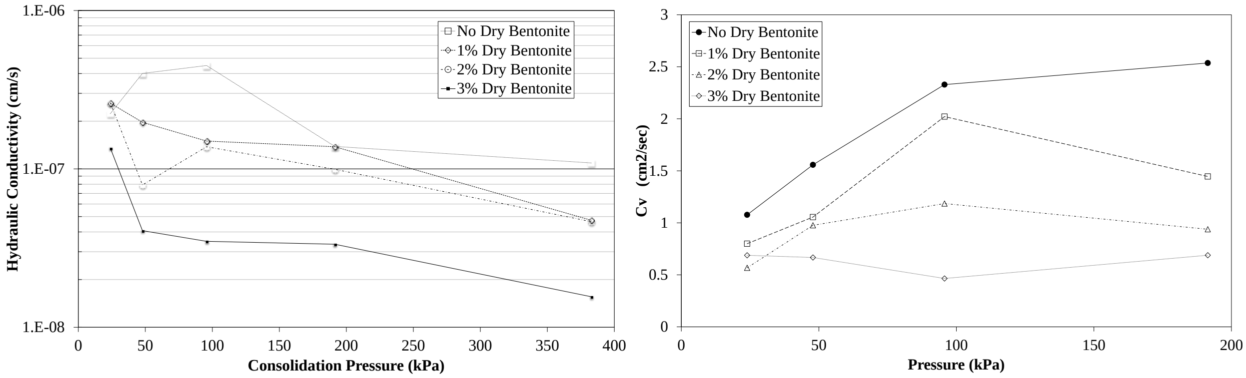

Figure 3. Hydraulic conductivity and coefficient of consolidation vs. consolidation stress

The results of the site characterization and backfill design programs were used as the basis for development of design plans for construction of the wall. The plans were prepared in accordance with appropriate standards of practice and addressed the following major components:

- construction coordination, equipment set-up, and site layout;
- equipment specifications (e.g., for excavation, backfill and slurry mixing);
- procedures for slurry mixing, trench excavation, backfill mixing, and backfilling;
- specifications for the sodium bentonite clay;
- rproperties of the bentonite-water slurry (i.e., viscosity, mud density, filtrate loss, and pH);
- required backfill proportions and properties (e.g., slump);
- specifications for the mixing water;
- requirements for construction quality control testing; and
- lines, grades, width, and tolerances for trench excavation.

Construction and instrumentation. Geo-Solutions, Inc. of New Kensington, PA, Bucknell's industry partner for this study, completed construction of the wall in July 2016. Construction followed standard operating methods with a slurry mixing pond, a tracked excavator to dig the trench and a bulldozer to mix the backfill. The wall is 194 m long and 0.9 m wide, installed to an average depth of approximately 7 m and a maximum depth of 8 m.

Instrumentation within and around the wall installed prior to, during, and/or shortly after construction includes:

1) inclinometers installed at eight locations immediately outside the trench to measure lateral deformations as a function of depth
2) earth pressure cell cages to measure the three-dimensional state-of-stress within the backfill installed at three depths at one location and a matching depth at a second location to examine reproducibility
3) paired sensors to measure moisture content and suction within the backfill
4) settlement plates to measure vertical deformation as a function of time
5) piezometers inside the wall to measure water levels and to perform *in situ k* testing of the backfill (by slug testing)
6) monitoring wells outside the wall (adjacent to the piezometers).

PRELIMINARY RESULTS

Inclinometers. The plot in the bottom right of Figure 4 presents the lateral displacement over time for one of the eight inclinometers installed. Although difficult to read, these data show a maximum inward movement (towards the trench) of almost 33 mm to date with movement continuing.

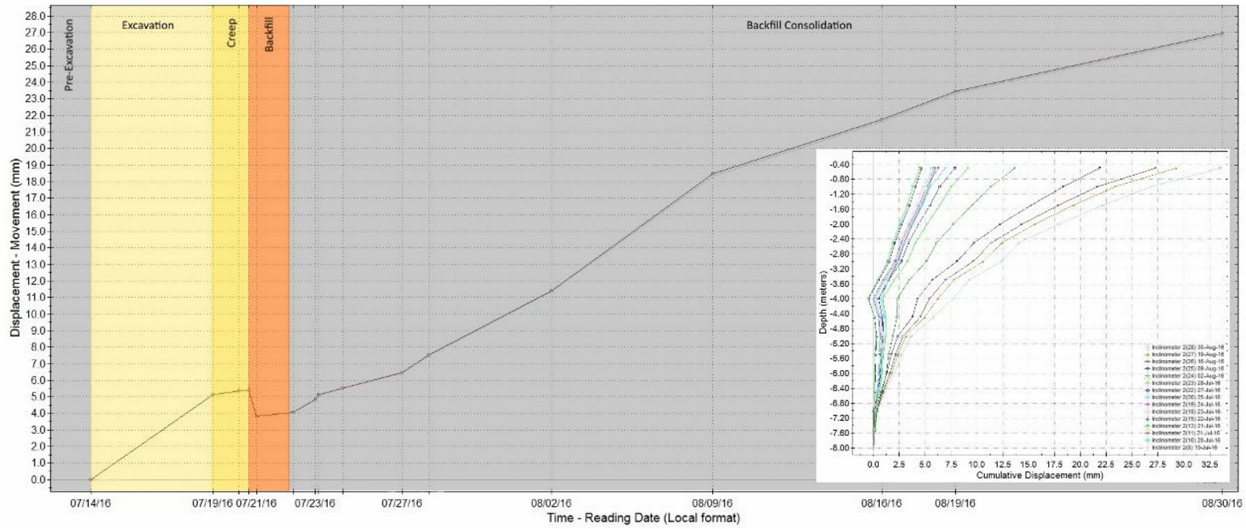

Figure 4. Inclinometer readings as a function of time

For illustrative purposes, the movement at a depth of 1.0 m was extracted and replotted on the left side of Fig. 4. Also shown on this Figure are the major events corresponding to the dates, including pre-construction, excavation, creep after excavation but prior to backfilling, backfilling and backfill consolidation with time. All of Fig. 4 is a direct output from the monitoring equipment and is admittedly difficult to read. A review of Fig. 4 would indicate the trench walls moved inward during and after excavation under a head of slurry. Backfill has a unit weight of almost twice that of the slurry yet behaves as a thick viscous liquid and the data show the wall moving back outward upon backfill placement. Since that time, the backfill is consolidating, transferring load to the sidewalls of the trench, and the sidewalls are moving inward mobilizing an increasing amount of shear strength in the backfill as the formation soil moves towards an active state-of-stress.

Earth pressure cells: The stress distribution in the experimental cutoff wall is being measured directly using earth pressure cells deployed at three different depths (2, 4, and 6 m) at one location and at a second location (6 m). Earth pressure cell cages were placed within the wall prior to backfill placement to measure the three-dimensional stress state (i.e., the vertical stress and the horizontal stresses in the transverse and longitudinal directions) within the backfill continuously over time.

The earth pressure cell cage (see left side of Figure 5) used in this study included three vibrating wire stress sensors mounted in three cardinal directions to measure vertical and horizontal (longitudinal and transverse) stresses. Each cage also has one vibrating wire piezometer to measure pore pressure, a biaxial tiltmeter to measure pitch and roll, and a magnetic compass to measure the as-placed orientation. The cages were originally designed for use in mine paste backfill and, therefore, have an open structure that is ideal for allowing the fluid SB backfill to fill the cage and cover the sensors. In order to deploy the cages at the desired depth and location, a steep pipe frame was designed and installed as shown on the right side of Figure

5. The cages and intermediate x-bracing were lowered though the slurry and held in place while the backfilling progressed. The pipe ends were sharpened to a point and embedded in the clay at the bottom of the trench to prevent movement during backfilling. The top of the pipe structure was also restrained from movement by tying off to weights located near the trench. Once backfilling was complete, the cages were released from their vertical constraints to allow them to settle with the backfill.

Figure 5. Photographs of earth pressure cell and cage (RST Instruments, BC, Canada)

Representative data from an earth pressure cell installed at 6 meters is shown on Fig. 6. All data is obtained via wireless transmission from the site to Bucknell University where it is downloaded to an online "dashboard" which allows the research team to examine the data at any time from any device connected to the internet. Figure 6 is a screen shot so the readers can see what the researchers see. Figure 6, all in terms of total stress, shows the initial stress due to the slurry, the increase in stress due to the backfilling on July 21st and the subsequent gentle decline in total stress at the backfill consolidates and transfers load to the side walls. The small bumps are due to various identifiable actions such as the addition of 0.3 m of cover in early September.

The stress measurements are complemented with measurements of vertical and horizontal deformations obtained from the settlement plates and inclinometers, respectively. These cages, and associated deformation data will allow for a complete assessment of the state-of-stress in all three directions with the results being used to validate, revise or develop new mathematical models of stress-state in SB walls. Note that two months in, 90% consolidation has not yet occurred and the time to consolidation is substantially greater than predicted.

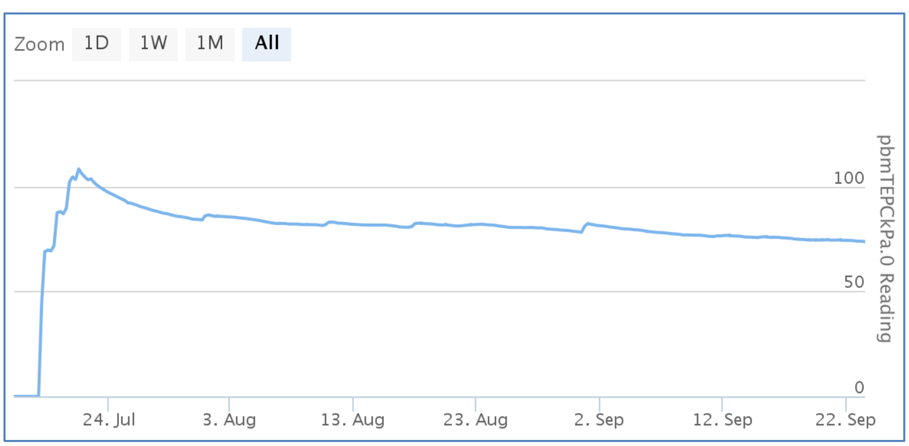

Figure 6. Total longitudinal stress at a depth of six meters

CONCLUSIONS

This paper describes the basis for and overview of an SB wall designed, constructed and instrumented for the express purpose of field study, specifically for assessing the *in situ* properties of the wall as a function of time and depth. The design, construction, instrumentation, and preliminary results of this research project are described to serve as a foundation for subsequent companion papers that will provide more detailed descriptions of the instrumentation installation procedures, instrumentation operation, data collection, and data analysis.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of the National Science Foundation (Award # 1463198) that enabled this research project and the co-Pi's on the project, Professors Michael Malusis and Robert Jacob. The authors would also like to acknowledge the contributions of CETCO which donated the bentonite for this project, Central Builders Supply which provided onsite support during construction and the study location, and Geo-Solutions, Inc. which performed the construction. The project would not have been possible without the support of these companies. In addition, the authors acknowledge the Jeffrey C Evans Geotechnical Engineering Laboratory endowment, established through the generosity of Michael and Laureen Costa, which was used to provide financial support for the students and faculty. Special thanks is also given to James Gutelius, Director of Bucknell's Civil Engineering Laboratories, for his numerous contributions to this project and to Professor Alan Marchiori for his contributions to the data acquisition and transmission. Contributing students include Ushma Manadhar, Brian Ward, Tyler Zbytek, Max Ororbia, Fernando Andrade Orellana Alves, Nancy Ingabire Abayo, and Landon Barlow. Special thanks goes to Max Ororbia for his work with the inclinometers. Finally, the authors appreciate the detailed reviews and helpful comments received as part of ASCE's peer review process.

REFERENCES

Britton, J.P., Filz, G.M., and Herring, W.E. (2004). Measuring the hydraulic conductivity of soil- bentonite backfill. *Journal of Geotechnical and Geoenvironmental Engineering*, 130(12), 1250-1258.

Evans, J.C. (1993). Vertical cutoff walls. *Geotechnical Practice for Waste Disposal*. D.E. Daniel, ed., Chapman and Hall, London.

Evans, J.C. (1994). Hydraulic conductivity of vertical cutoff walls. *Hydraulic Conductivity and Waste Contaminant Transport in Soils, ASTM STP 1142*, D. E. Daniel and S. J. Trautwein, eds., American Society for Testing and Materials, Philadelphia, 79-94.

Evans, J.C. (1995). Soil- and cement-based vertical barriers with focus on materials. *Assessment of Barrier Containment Technologies – A Comprehensive Treatment for Environmental Applications*.

Evans, J.C. and Ryan, C.R. (2005). Time-dependent strength behavior of soil-bentonite slurry wall backfill. *Waste Containment and Remediation: Proceedings of the Geo-Frontiers 2005 Congress,* ASCE Geotechnical Special Publication No. 142.

Evans, J.C. Costa, M. and Cooley, B. (1995). The state of stress in soil-bentonite slurry trench cutoff walls. *ASCE Specialty Conference on Characterization, Containment, Remediation* *and Performance in Environmental Geotechnics, The Geoenvironment 2000,* ASCE Geotechnical Special Publication No. 46.

Evans, J.C., Fang, H.Y., and Kugelman, I.J. (1985). Containment of hazardous materials with soil- bentonite slurry walls," *Proceedings of the 6th National Conference on the Management of Uncontrolled Hazardous Waste Sites*, Washington, D.C., November, 1985, 249-252

Evans, J.C., Malusis, M.A. and Jacob, R. (2014) Field Testing and Monitoring of an Experimental Soil-Bentonite Cutoff Wall, Proposal to the National Science Foundation, Award # 1463198

Filz, G.M. (1996). Consolidation stresses in soil-bentonite back-filled trenches. *Proceedings of the 2nd International Congress on Environmental Geotechnics,* M. Kamon, ed., Osaka, Japan, 497-502.

Filz, G.M., Baxter, D.Y., Bentler, D.J., and Davidson, R.R. (1999). Ground deformations adjacent to a soil-bentonite cutoff wall. *Proceedings, Geo-Engineering for Underground Facilities,* ASCE Geotechnical Special Publication 90, 121-139.

Malusis, M.A., Yeom, S., and Evans, J.C. (2011). Hydraulic conductivity of model soil-bentonite backfills subjected to wet-dry cycling. *Canadian Geotechnical Journal*, 48(8), 198-211.

Millet, R.A., Perez, J.Y., and Davidson, R.R. (1992). USA Practice Slurry Wall Specifications 10 Years Later. *Slurry Walls: Design, Construction, and Quality Control*, ASTM STP 1129, Paul, Davidson and Cavalli, Eds., American Society for Testing and Materials, Philadelphia, PA, 42-68.

Millet, R.A. and Perez, J.Y. (1981). Current USA Practice: Slurry Wall Specifications. *Journal of the Geotechnical Engineering Division,* ASCE, 107(GT8), 1041-1056.

National Research Council (2007). *Assessing the Performance of Surface and Subsurface Engineered Barriers.* National Academies Press, Washington, D.C.

Ruffing, D. G., and Evans, J. C., (2010). In situ evaluation of a shallow soil-bentonite slurry trench cutoff wall. *Proceedings of the 6th International Congress on Environmental Geotechnics*, New Delhi, India, Tata McGraw-Hill, ISBN 13:9780070707108, 758-763.

Ruffing, D.G., Evans, J.C., and Malusis, M.A. (2010). Prediction of earth pressures in soil-bentonite cutoff walls. *GeoFlorida 2010: Advances in Analysis, Modeling, and Design*, ASCE Geotechnical Special Publication 199, 2416-2425.

Ryan, C.R. and Day, S.R. (2003). Soil-bentonite slurry wall specifications. *Pan American Conference on Soils Mechanics & Geotechnical Engineering, ASCE Geo-Institute and MIT, Cambridge, MA*, 8 p.

Shackelford, C.D. (1994). Waste-soil interactions that alter hydraulic conductivity. *ASTM STP 1142, Hydraulic Conductivity and Waste Contaminant Transport in Soil*, D.E. Daniel and S.J. Trautwein, eds., 111-168.