Stresses in Soil-Bentonite Slurry Trench Cutoff Wall

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ABSTRACT

Soil bentonite (SB) slurry trench cutoff walls have been widely used for over 40 years to control ground water flow through and beneath dams and levees and to control subsurface contaminant transport at contaminated sites. The idea that the state-of-stress in SB slurry trench cutoff walls is less than geostatic was first published over 30 years ago and it is well established that the hydraulic conductivity of SB backfill is stress dependent. With funding from the National Science Foundation, a full-scale, instrumented SB slurry trench cutoff wall was constructed with embedded instrumentation that directly measures the stress and pore pressure in three dimensions at multiple depths and locations. These data have been synthesized and the authors compare the results of stress measurements in this wall with various models. Finally, the authors provide summary opinions and practical recommendations for the design and construction of SB walls.

INTRODUCTION

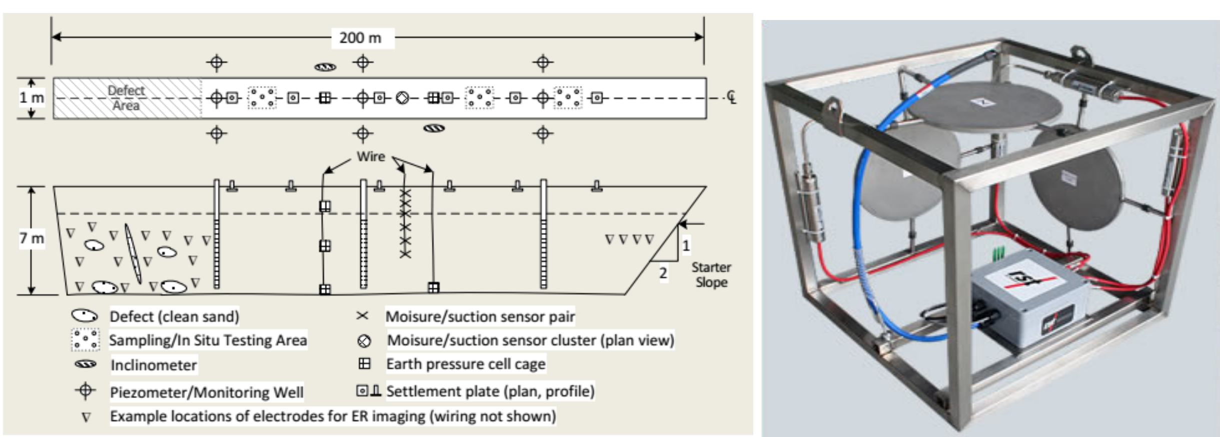
Soil bentonite (SB) slurry trench cutoff walls have been widely used in the US and abroad for over 40 years to control ground water flow through and beneath dams and levees and to control subsurface contaminant transport at landfill and industrial sites. The idea that the state-of-stress in SB slurry trench cutoff walls is less than geostatic was first published over 30 years ago (Evans et al. 1985). This concept has since been evaluated numerous times, for example as described in Evans et al. (1995), Filz (1996), and Ruffing et al. (2010). An understanding of the state-of-stress is important because laboratory permeability tests on SB backfills were and are often inappropriately conducted at stresses estimated using a geostatic calculation. Given the known relationship between higher consolidating stresses and lower values of hydraulic conductivity of SB backfill, it is important to know if the state-of-stress is lower than a geostatic calculation would predict so as to conduct laboratory tests at appropriate stresses. Many of the *in situ* testing and sampling studies performed to test the "lower than geostatic" hypotheses have been focused on leveraging opportunities at existing SB cutoff wall sites (for example, see Ruffing and Evans 2010, Ruffing et al. 2010). Due to site access limitations and limited funding, these studies were constrained in both scale and duration. In addition to field and laboratory testing, numerous models have been proposed to predict the stress state, including closed form and iterative solutions (Evans et al. 1995, Filz 1996, Ruffing et al. 2010) as well as finite element modelling (Li et al. 2015). The difficulty has been in validating and testing these models against *in situ* stress measurements. With funding from the National Science Foundation (NSF), a full-scale, fully-instrumented SB slurry trench cutoff wall was constructed in 2016 with embedded instrumentation that enabled direct measurement of the total stress and pore pressure in three dimensions at various depths and multiple locations. At the time of this writing, this wall has been monitored over a period of nearly two years. In addition to direct stress measurements, *in situ* tests, including vane shear and cone penetration tests, have also been conducted. This paper presents a synthesized set of data from this wall and the authors compare the results of stress measurements in this wall to the predictions from various models. Finally, and most importantly, the authors provide summary opinions and reinforce practical recommendations for the design and construction of SB walls.

SB CUTOFF WALL CONSTRUCTION

The construction and instrumentation for the SB cutoff wall studied for this paper are described in detail elsewhere (Malusis et al. 2016, Evans and Ruffing 2017, Evans et al. 2017 and Evans et al 2018). For ease of reference, a brief overview is provided here. The SB cutoff wall constructed for this work was installed in Montandon, PA at a site near Bucknell's campus in the Summer of 2016. This cutoff wall is approximately 200 m long, 7 m deep, and 0.9 m wide. The site is adjacent to the Susquehanna River and is underlain by a pinnacled shaley limestone. Overlying the bedrock is a layer of clay varying in sand content and thickness (1 to > 5 m). Above the clay is a layer of silty sand and gravel with occasional cobbles with an average thickness of 4 to 5 m. Finally, a layer of sandy topsoil approximately 0.5 m thick covers the site.

MEASUREMENTS

A key feature of this project was the extensive instrumentation installed in and around the wall, including earth pressure cells, pore pressure transducers, inclinometers and monitoring wells as shown in Fig. 1.a. Instrumentation cluster cages (see Fig. 1.b.) were installed at depths of 2, 4 and 6 m at station 0+84 and at a depth of 6 m at station 0+75. These instrumentation clusters were fitted with roll, pitch and orientation sensors so that all earth pressure readings could be corrected for small variations in instrumentation alignment. Data is regularly transmitted from the sensors to the data acquisition unit via hard wiring and subsequently transmitted wirelessly to a receiver on Bucknell University's campus. The data is then downloaded to a publicly availably dashboard (http://www.eg.bucknell.edu/eswapp/index.html).



(a) (b)

Figure 1. (a) Plan and cross-section of SB wall with instrumentation. (b) Instrumentation cluster.

Inclinometer readings to measure the horizontal movement of the ground adjacent to the cutoff wall were taken prior to the start of construction, during construction, after construction, and long after construction, most recently in June 2018.

Earth Pressure Cells. The time history of stress development and lateral deformation for the first fifteen months of data for this study has been presented elsewhere (Evans et al. 2017). The focus of this paper is the state-of-stress nearly two years after wall construction, presumably "steady state" conditions, and a comparison of the measured stress with various models for stress prediction in SB slurry trench cutoff walls. Fig. 2 shows a recent (30 May 2018) evaluation of the effective stress measured in each cage for three dimensions (vertical, transverse, and longitudinal) plotted vs. depth.

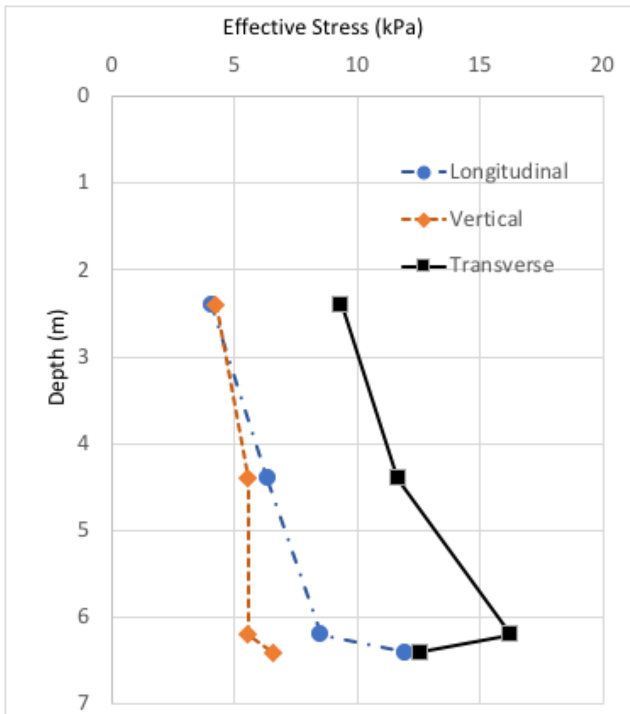


Figure 2. Effective stresses in SB backfill.

Several observations are worthy of note from these field measurements. Firstly, the highest value of effective stress measured was 16.2 kPa (2.3 psi) for the transverse stress at a depth of 6.2 m. The highest vertical effective stress measured was 5.5 kPa (0.8 psi). Note that the vertical effective stress of 5.5 kPa (0.8 psi) is much less than a vertical effective stress calculated using geostatic conditions of 85 kPa (12.3 psi). Secondly, the largest effective stress is measured in the transverse direction which is consistent with a rotation of principle stresses. The principle stress rotation is theoretically supported by the anticipated effects of arching that reduces the vertical stress and inward movement of the trench sidewalls that increases the transverse stress. Thirdly, the vertical stress is lowest for each of the instrumentation clusters which is consistent with expectations from the arching model. Finally, the longitudinal stress appears to result from the plane strain condition along the wall.

Inclinometers. Inclinometer measurements, specifically those taken after primary consolidation of the backfill was expected to be complete, can also be used to back-calculate the expected stresses in the backfill using the measured deformations and a stress-strain relationship for the backfill (see Evans et al. 2017). Plots of deformation versus depth as a function of time for the inclinometers nearest the earth pressure cells are shown on Figure 3. Note that the inward movement continues (albeit at a slow rate) even nearly two years after the wall was completed. Past studies have shown (Evans and Ryan 2005), that SB backfill continues to consolidate after primary consolidation is complete, i.e. secondary consolidation, both vertically and laterally at an ever-decreasing rate.

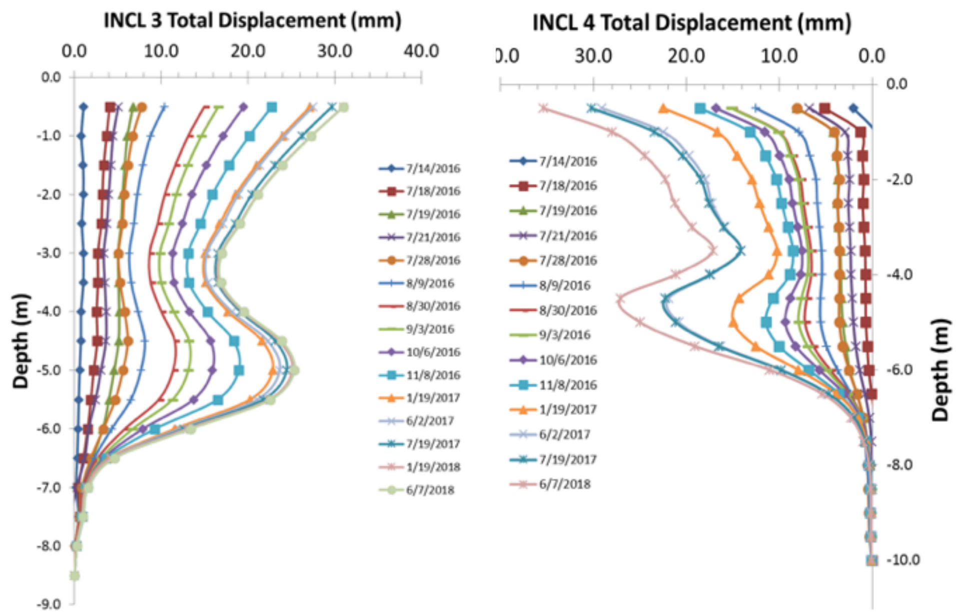


Figure 3. Inclinometer deflections from inclinometer pair closest to the earth pressure measurements.

STRESS PREDICTION MODELS

Ruffing et al. (2010) provides a detailed overview of the two original SB stress prediction models, termed therein as the Arching and the Lateral Squeezing (LS) models and goes on to present an improved version of the LS model termed the Modified Lateral Squeezing (MLS) model.

Arching. The Arching model, originally proposed in Evans et al. (1995), assumes rigid sidewalls and stress development in the wall is controlled by the self-weight consolidation of the backfill, including the effects of friction between the backfill and the trench sidewalls, hence the “arching” designation. This model is theoretically very similar to the models used to determine stresses above and below buried pipelines. Depending on the input parameters selected (low vs. high stress cohesionless backfill or even a cohesive backfill), the Arching model predicts a horizontal effective stress of 2.5 to 12.5 kPa at the mid-point of this wall (3.5 m) and 5 to 15 kPa at the bottom (7 m).

Lateral Squeezing. The LS model, proposed in Filz (1996), allows for consolidation of the SB backfill resulting from inward movement of the sidewalls. The MLS model (Ruffing et al. 2010) builds on the theory behind and practical use of the LS model by accounting for the stress dependent nature of SB backfill compressibility and providing reference tables and charts needed for calculations. Depending on the assumed soil conditions outside of the wall at this site (a major influence in the MLS model), the MLS model predicts a horizontal effective stress of 7.5 to 12.5 kPa at the mid-point of this wall (3.5 m) and 12.5 to 25 kPa at the bottom (7 m).

Finite Element. More recently, efforts to model the stress in SB walls using finite element have been undertaken, most notably as described in Li et al. (2015). In the referenced study, the authors consider the arching effect via force equilibrium and the lateral squeezing effect due to the inward movement of the trench sidewalls via a Winkler idealization. In that paper, the resulting stress prediction is compared to and matches well with a deep SB stress data set from Ruffing et al. (2015). While the model was not run for the specific parameters for the SB wall described herein, a comparison of values from this model with field measured values show the model predicts higher stresses than those measured and shown in Fig. 2.

Braced Excavation in Sand. In addition to the models specifically developed for prediction of stresses in SB walls, it is also interesting to compare the stresses within the slurry trench cutoff wall with those published by Peck (1969) for braced excavations in sand (see Fig 4). The Peck earth pressure distribution results from soil-structure interaction where the excavation proceeds from top down and the support (bracing) is placed as the excavation proceeds. The "excavation and support" process from the top down is similar for both the braced excavation and the SB slurry trench cutoff wall studied for this investigation. This process differs from that for a retaining wall earth pressure diagram where fill being placed from the bottom up and the resulting earth pressure diagram is triangular. Also note the constant earth pressure with depth for a supported excavation in sand. Peck (1969) recommends the earth pressure be calculated as:

$$Pa = 0.65 \, \gamma \, H \, K_a \qquad \text{Eq. 1}$$

Where H is the height of the wall, γ is the unit weight of the material being supported and Ka is the active earth pressure coefficient of the material being supported. Using site specific data for this wall ($H = 7$m, $\gamma' = 10$ kPa and $\phi = 34^o$) and inputting into Eq. 1 results in a computed earth pressure of 12.9 kPa.

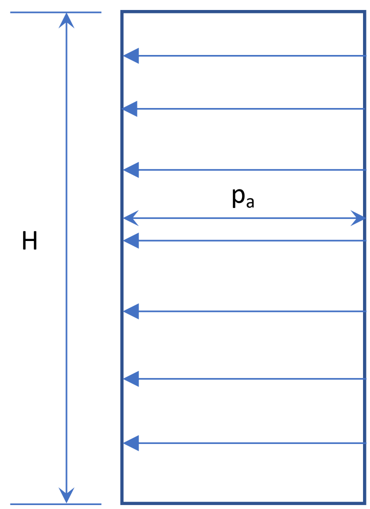


Fig. 4 Apparent earth pressure diagram for a braced cut in sand (After Peck 1969)

RESULTS AND DISCUSSION

Fig. 5 shows, as a function of depth, the measured transverse stress, calculated transverse stress from inclinometer measurements and calculated transverse stress from several models, and the vertical geostatic stress commonly used by designers to assign stresses for use in laboratory permeability tests.

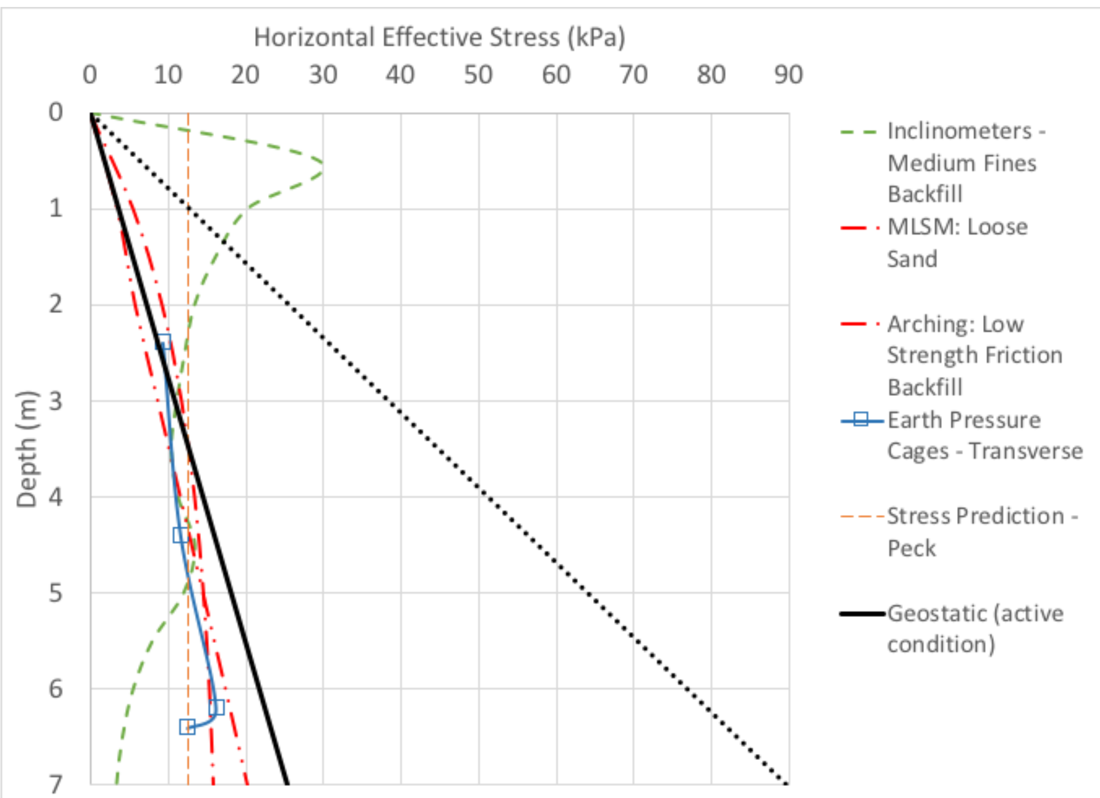


Figure 5. Stress Predictions and Measurements for the Subject SB Cutoff Wall.

A review of Fig. 5 shows that there are clearly differences in predicted stresses between the models, the direct stress measurements from the stress cells, and the back-calculated values from the inclinometer readings. However, from a practical standpoint the most important lesson is that the horizontal earth pressures (consolidation stress) at depths greater than about 3 m can be substantially lower than those calculated using geostatic assumptions. Importantly, many labs, even those familiar with permeability testing SB backfill samples, will default to a consolidation stress of 35 kPa to 70 kPa (5 to 10 psi). As shown in Fig. 5 and supported by data presented in many of the references included herein, actual measured stresses could be a half or a full order of magnitude lower than the stress computed using a geostatic calculation and may even be lower than the stress calculated using models developed for stress calculation in SB walls.

A simple calculation using an existing earth pressure theory developed for a different, but in many ways similar, application resulted in a stress prediction that is well within the expected range. This indicates that a rough indication of the stress in an SB wall may be obtained using Peck's method for calculating the stress on a braced excavation. This equation is applicable to a SB installation in a cohesionless formation soil.

LIMITATIONS, SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The authors acknowledge that the data from this study is limited by the relatively shallow depth of the wall and the lack of significant measurement redundancy, but the practical implications are clear. The use of comparatively high consolidation stresses in the laboratory to measure the hydraulic conductivity of SB backfill is inappropriate and will result in an unrealistically low hydraulic conductivity measurement for such relatively stress sensitive material. Given that the state-of-stress within an SB wall is considerably less than geostatic, it is important to design a SB backfill using a wide range of grain sizes, i.e. a "well-graded" backfill, to minimize the stress dependence of the backfill hydraulic conductivity. There is an increasing body of knowledge demonstrating the relatively low stresses in SB backfill and, while there is some variation from site to site and study to study, there is no doubt the stresses are considerably less than geostatic. This must be incorporated into design and testing conditions for SB cutoff walls. In the absence of site specific calculations, and especially for shallow walls installed in cohesive soils, permeability testing on SB backfills should be performed at an effective consolidating stress of not more than 20 kPa (3 psi).

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REFERENCES

Evans, J. C., Fang, H. Y., and Kugelman, I. J., "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, pp. 249-252.

Evans, J. C. Costa, M. and Cooley, B., "The State of Stress is 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, February, 1995.

Evans, J.C. and Ruffing, D.G. (2017) "Design and Construction of an Experimental Soil-Bentonite Cutoff Wall." *ASCE Geotechnical Frontiers 2017,* ASCE GSP 277, pp. 164-174.

Evans, J. C., Yang, Y.-L., and Ruffing, D.G. (2018) Vane Shear Tests to Evaluate In Situ Stress State of a Soil-Bentonite Slurry Trench Wall, *Proceedings of the 8th International Congress on Environmental Geotechnics*, Hangzhou, China, October 28 to November 1, 2018.

Evans, J. C., Ororbia, M., Gutilius, J., Ruffing, D.G., Barlow, L., Malusis, M.A. (2017) "Soil-bentonite slurry trench cutoff wall lateral deformations, consolidation, stress transfer and hydraulic conductivity" *Proceedings of the 2nd Symposium on Coupled Phenomena in Environmental Geotechnics (CPEG2), Leeds, UK.*

Filz, G.M. (1996). "Consolidation stresses in soil-bentonite back-filled trenches." *Proc., 2nd Int. Congress on Env. Geotechnics,* M. Kamon, Ed., Osaka/Japan, 497-502.

Li, Y-C., Cleall, P.J., Wen, Y-D., Chen, Y-Mi. and Pan, Q. (2015) "Stresses in soil-bentonite slurry trench cutoff walls" *Geotechnique* 65 (10), pp. 843-850

Malusis, M.A., Evans, J.C., Jacob, R.W., Ruffing, D.G., Barlow, L.C., and Marchiori, A.M. (2002) "Construction and Monitoring of an Instrumented Soil-Bentonite Cutoff Wall: Field Research Case Study, *Proceedings of the 29th Central Pennsylvania Geotechnical Conference*, Hershey, PA, January.

Ruffing, D. G., and Evans, J.C., (2015) "Strength and Stress Estimation in Soil Bentonite Slurry Trench Cutoff Walls using Cone Penetration Test Data." *The International Foundations Congress and Equipment Expo, San Antonio Texas* ASCE GSP 256, pp. 2567-2576.

Ruffing, D. G., and Evans, J. C., "In Situ Evaluation of a Shallow Soil Bentonite Slurry Trench Cutoff Wall" *Proceedings of the 6th International Congress on Environmental Geotechnics*, New Delhi, India, November 8-12, 2010, Tata McGraw-Hill ISBN 13:9780070707108, pp. 758-763.

Ruffing, D. G., Evans, J. C., and Malusis, M. A., (2010) "Prediction of Earth Pressures in Soil-Bentonite Cutoff Walls," *ASCE GeoFlorida 2010 Advances in Analysis, Modeling and Design GSP 199,* pp. 2416-2425.