Vane Shear Tests to Evaluate In Situ Stress State of a Soil-Bentonite Slurry Trench Wall

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Abstract. Soil-bentonite slurry trench cutoff walls have been employed widely in the US as engineered barriers to control groundwater flow and contaminant migration in the subsurface. The hydraulic conductivity of the soil-bentonite backfill is stress dependent and to better understand the in-situ stress state of soil-bentonite slurry trench walls, a wall with a length of 194 m, depth of 7 m, and width of 0.9 m was constructed, instrumented, and investigated in-situ. As a part of the in-situ investigation, vane shear tests were conducted at different locations and depths to evaluate the shear strength distribution within the wall. The results indicate that the peak undrained shear strength value, S_u, exhibits a consistent trend with increasing depth. In general, two stages of S_u were observed: (1) at depth from 1 to 2.5 m, the S_u decreases as depth increases, presumably due to the effects of the cover soil and groundwater level; (2) at depth of 2.5 to 7 m, the S_u shows insignificant change with depth and falls into the range of 5 to 10 kPa. Using a constant shear strength to effective stress ratio, S_u/σ', the stresses predicted from the vane shear strength tests were in good agreement with those measured using earth pressure sensors embedded at the time of wall construction.

Keywords: Bentonite, Shear strength, Slurry trench wall, State of stress, Vane shear test.

1.1 Introduction

Soil-bentonite (SB) slurry trench cutoff wall backfill is commonly composed of a blend of in-situ excavated or borrow soil and slurry made from sodium bentonite and water. These cutoff walls have been employed widely in the US and Canada as engineered barriers to control the migration of groundwater as well as subsurface contaminants (D’Appolonia 1980; Evans 1993; Sharma and Reddy 2004). Construction steps include subsurface trench excavation under bentonite-water slurry, and then replacement of the slurry within the trench by SB backfill. As a seepage control structure, hydraulic conductivity of the wall is considered to be one of the major principle performance criterions, and its upper limit value is commonly specified as 1×10^{-9} m/s.

Hydraulic conductivity of the SB backfill is known to be stress dependent. Hydraulic conductivity decreases with increasing effective stress (Evans 1994; Shackelford 1994; Filz et al. 2001; Ruffing and Evans 2010; Evans and Huang 2016). Therefore, reliable estimation of the stress-state within the wall is of critical importance. However, there are a limited numbers of studies, particularly field studies, addressing the in-situ stress state of SB walls (Ruffing et al., 2010; Ruffing and Evans 2010; Ruffing et al. 2011; Ruffing et al., 2015). Based on the above considerations, a SB wall was constructed, instrumented, and investigated at a site located 3 km east of the Bucknell University campus in Lewisburg, PA. Post installation, the wall has been subjected to a series of field and laboratory tests to investigate the barrier integrity, state-of-stress in the wall, and backfill properties. As a part of these investigations, vane shear tests were conducted in June to July 2017 at eight locations to evaluate the in-situ shear strength of the wall.

This paper presents results of the in-situ vane shear tests. Variations of the undrained shear strength (S_u) at different locations and depths are presented. A S_u to effective vertical stress ratio (S_u/σ') is suggested based on the stress measured by the earth pressure sensors.

1.2 Cutoff Wall Site and Backfill Properties

The SB cutoff wall was set within a buffer zone between a permitted mining area of a commercial sand/gravel quarry, operating by Central Builders Supply, and a natural wetland known as the Montandon Marsh (Fig. 1). The subsurface of the project site consists of primarily alluvial materials within the footprint of historic flooding and river channels of the Susquehanna River. The wall, with a length of approximately 194 m, width of 0.9 m, and average depth of approximately 7 m, was constructed in July 2016 by Geo-Solutions, Inc., New Kensington, PA, USA. The constructed wall was covered by geotextile followed by 0.3 m of top soil on over the geotextile.

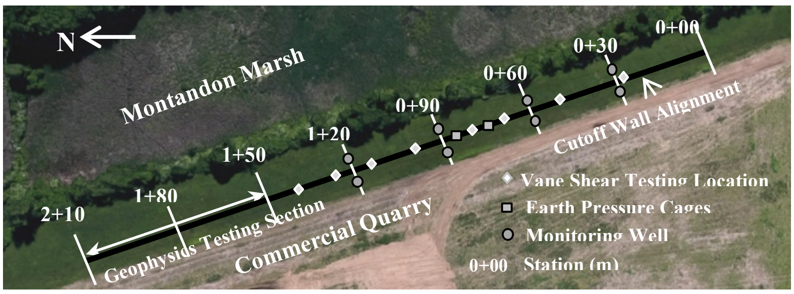

Fig. 1. Plan diagram of the cutoff wall with locations of the monitoring wells and the vane shear testing points.

The backfill within the wall consists of imported base soil from the mine site and enough 5% bentonite-water slurry to create a workable material. The resulting total bentonite content of the backfill is approximately 1%, weight of bentonite to weight of soil. The fines content in the backfill is found ranging from 44% to 54%. Laboratory measurements of grab samples of the backfill indicate that the hydraulic conductivity ranges from 7.0×10^{-10} to 1.4×10^{-9} m/s as tested in flexible-wall triaxial tests under 21 kPa or 35 kPa effective stress condition. For more details, please see Evans and Ruffing (2017) and Malusis et al. (2017).

1.3 Vane Shear Tests

Vane shear tests were conducted at eight locations along the wall alignment, at an average distance interval of 16 m (Fig. 1). The vane shear tests were conducted in general accordance with ASTM D2573. Considering the softness of the backfill and to ensure acceptable torque resolution, a larger, custom-made field vane was selected. This vane has tapered tip with diameter of 0.089 m and vane height of 0.184 m consistent with the dimension ratios required by ASTM. The taper angles at the top and bottom of the vane are 47°.

The vane shear test was performed at increments of 0.5 meters until the blades reached a depth of approximately 7.0 m, the wall bottom. At each 0.5 m increment of depth, torque readings were taken using a digital torque wrench and used to calculate the S_u. As per ASTM, a slip coupling was used to determine rod friction. Average rotation rates of 0.1 degree per second were used with a variation of 0.05 to 0.2 degree per second, as permissible. The maximum torque value on the digital readout was used to calculate the shear strength based on below equation as per the ASTM D2573:

$$S_u = \frac{12 * T_{max}}{\pi D^2 * (\frac{D}{\cos(i_T)} + \frac{D}{\cos(i_B)} + 6H)} \quad (1)$$

Where S_u is the undrained shear strength, T_{max} is the maximum torque value, D is the diameter of the vane, H is the height of the vane, i_T is the angle of taper at the top of the vane, and i_B is the angle of taper at the bottom of the vane.

1.4 Stress Measurement

The stress distribution in the wall was measured using earth pressure sensors as shown in Fig. 2. The earth pressure sensors were mounted in an aluminum frame at transverse, longitudinal, and vertical directions to directly measure the total stress along with a pore pressure sensor to permit calculations of effective stress. In addition, pitch, roll and direction sensors were mounted on the frame to correct stress measurements for placement orientation. A total of four frames were installed, with three placed at 0+84 at depths of 2.4 m, 4.4 m, and 6.4 m, and one placed at 0+75 at depth of 6.2 m. For more information regarding the instrumentation, please see Evans and Ruffing (2017) and Malusis et al. (2017).

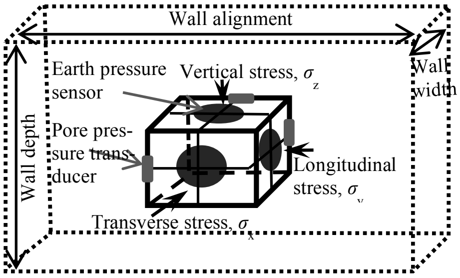

Fig. 2. Diagram of earth pressure cage installed within the trench wall.

2 Results and Discussion

2.1 Undrained Shear Strength

A correction factor of 0.92 was used to correct the raw field S_u, as per ASTM D2573 and based on the plasticity index of the backfill of 7 (Malusis et al. 2017). The variations of the resultant S_u values with depth at eight different locations of the wall are shown in Fig. 3. In general, the S_u value at 1 to 7m depth ranges from 3.9 to 14.8 kPa, which is consistent with the magnitude of shear strength results reported from other SB walls, e.g. Ruffing and Evans (2010) and Evans and Ryan (2005). Anomalous data points are marked with the "?" sign in Fig. 3. These anomalous points show S_u values that are substantially higher than the other data and are attributed to the presence of occasional oversize gravel and cobbles within the backfill. The groundwater levels presented in Fig. 3 were obtained from adjacent groundwater monitoring wells by linear interpolation.

As shown in Fig. 3 the S_u values at the eight different locations exhibit a consistent trend with respect to depth. Two distinct regions of S_u are shown: (1) the S_u decreases from about 13 kPa to 7 kPa as depth increases from 1 to 2.5 m; (2) at depths of 2.5 to 7 m, the S_u shows insignificant change with depth, and falls into the range of 5 to 10 kPa. The higher values of S_u near the top of the wall can be attributed to the localized effects of the weight of the cover soil and potentially suction pressures, this area is generally above the water table, from wet and dry cycles. Also, lateral deformation data from inclinometers installed along the sidewall alignment indicates that the maximum inward deformation occured at the top of the wall and little to no movement at bottom of the wall (Evans et al. 2017). All of these factors contribute to higher strength in the top 2.5 m of the wall. For depth of 2.5 to 7.0 m, less lateral deformation was observed, and expectedly the backfill within this depth exhibits relatively constant S_u values. At some testing locations, the trench bottom exhibits higher S_u values as compared to the backfill which is attributed to the vane penetrating into the native soil below the wall.

Fig. 4 shows a composite data set of the average undrained shear strength value, $S_{u,ave}$, vs. depth. It should be noted that the anomalous data points as marked in Fig. 3 are not included in the $S_{u,ave}$ value in Fig. 4. Fig. 4 clearly shows the trend of decreasing S_u within the first 2.5 m depth and a slight increasing trend from 2.5 m to 7.0 m depth.

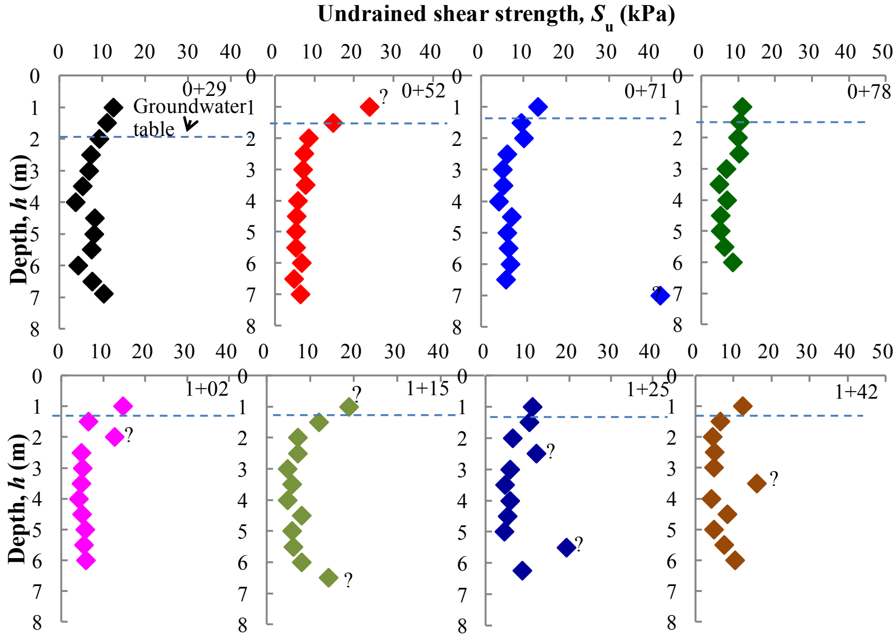

Fig. 3. Undrained shear strength at different test locations of the wall.

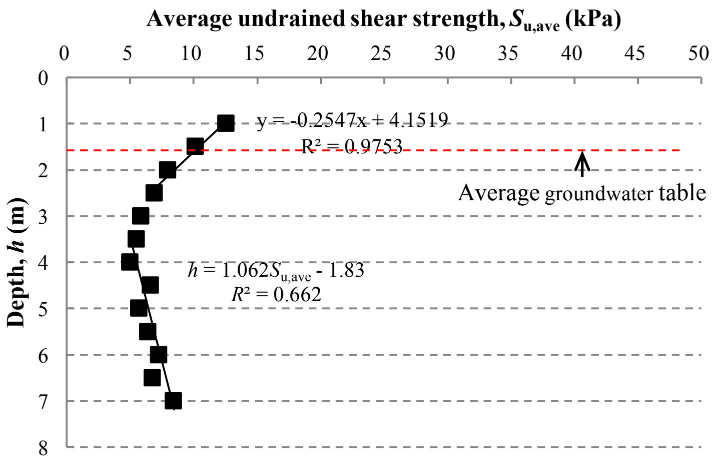

Fig. 4. Variation of average undrained shear strength with depth.

2.2 Relationship between Shear Strength and Effective Stress

Conventional soil mechanics can be used to directly relate to the effective confining stress (Lambe and Whitman 1969; Holtz and Kovacs 1981). Moreover, shear strength has been related to the major principle stress, normally the vertical effective stress, σ'_v, for normally consolidated (NC) soils in the form of S_u/σ'_v by many researchers (Lambe and Whitman 1969; Ruffing et al. 2015). Ruffing et al. (2015), shows that the S_u/σ'_v value ranges from 0.1 to 0.3. In that study, the authors selected a S_u/σ' value of 0.22 and 0.30 to predict horizontal effective stress in a SB wall.

The transverse, longitudinal, and vertical effective stresses of the study wall (denoted as σ'_x, σ'_y, and σ'_z, respectively) obtained from the pressure cells at 2.4 m, 4.4 m, and 6.4 m depths at location 0+80 and at 6.2 m depth of location 0+75 are plotted in Fig. 5. These data were collected one year after the wall construction. At both locations, both σ'_x and σ'_y increase, while σ'_z decreases as depth increases, with the horizontal effective stress (i.e., σ'_x and σ'_y) generally higher than the vertical one (i.e., σ'_z). The transverse effective stress, σ'_x, appears to be the major principle stress in this wall and is used to represent the horizontal effective stress (σ'_h) in following analysis. This is consistent with that determined by Ruffing et al. (2011) using Marchetti Dilatometer tests, and that assumed by Ruffing et al. (2015), who also indicated that the major principle stress is in the horizontal rather than the vertical direction within most SB walls.

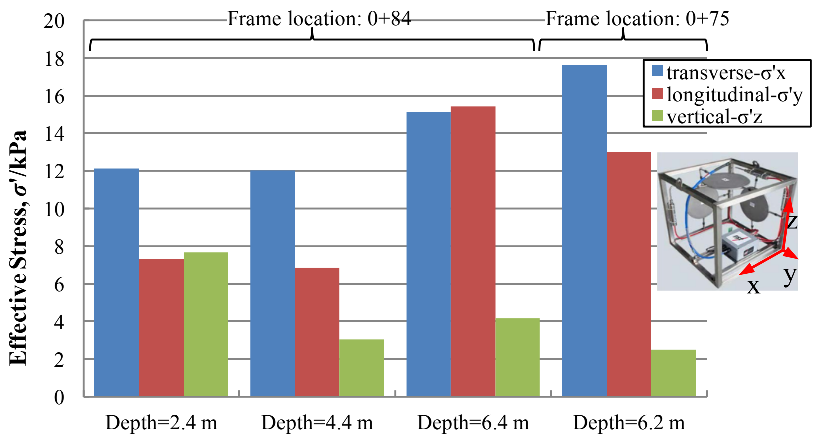

Fig. 5. Transverse, longitudinal, and vertical effective stresses at different depth in wall.

Fig. 6 displays the variation of measured σ'_x with wall depth. In addition, the predicted horizontal effective stresses, σ'_h, using $S_{u,ave}/\sigma'$ of 0.2, 0.3, 0.4, 0.5, and 0.6 also plotted in Fig. 6 for comparing purpose. The $S_{u,ave}/\sigma'$ values of 0.2 and 0.3 were chosen based upon Ruffing et al. (2015) and typical of normally consolidated soils in a typical sedimentary geologic environment. On average, the best fit occurs at $S_{u,ave}/\sigma'$ value of 0.5.

This analysis shows the stresses are lower than would be predicted using S_u/σ' ratios of 0.3, as would be expected from the literature. Another way to think of this result is that the measured strengths are higher than those predicted using S_u/σ' of 0.3.

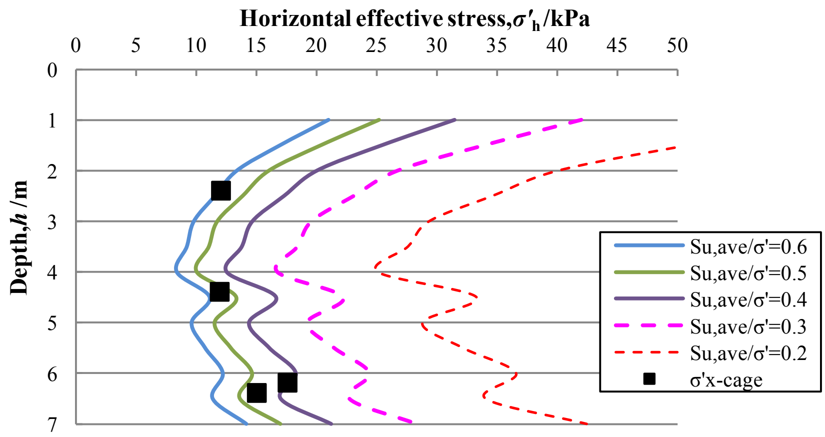

Fig. 6. Measured and predicted horizontal effective stress vs. depth.

3 Conclusions

A SB slurry trench cutoff wall was constructed, instrumented, and investigated. One of the investigation methods, the vane shear test, was performed for direct measurement of the shear strength with the ultimate purpose of calculating the state-of-stress within the wall. The vane shear data show a decrease in strength for the shallow portion of the wall (from 1 to 2.5 m in depth) due to a combination of factors including soil cover weight, wetting and drying, unsaturated stresses, and greater inward lateral movement near the top of the wall. Below 2.5 m, the shear strength is essentially constant until the bottom of the wall at a 7 m depth, with shear strength values between 5 to 10 kPa. Based on the measured effective stress using earth pressure sensors, the transverse effective stress, σ'_x, is found to be the major principle stress in the wall. A $S_{u,ave}/\sigma'$ value of 0.50 correlates will with the data in this study to associate the shear strength and effective stress.

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