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Soil-Bentonite Slurry Trench Cutoff Wall Final Design Report

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SOIL-BENTONITE SLURRY TRENCH CUTOFF WALL

SENIOR DESIGN REPORT

Ushma Manandhar, Brian Ward, and Tyler Zbytek

4/27/2015



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Executive Summary:

Bucknell University Geotechnical Engineering faculty members have a proposal seeking funding from the National Science Foundation (NSF) for the design, construction and long-term research of a soil-bentonite cutoff wall at Montandon Marsh. A team of three senior civil engineering students at Bucknell were tasked with completing the design portion of this proposal for their senior design project. The group conducted a detailed site investigation including two site borings and laboratory soil classification tests. Next, the group created four potential mix designs using a composite soil mix representative of the soil stratification on site. After consolidation and permeability testing on these soil mixes and calculation of the *in-situ* vertical effective stress, the project team chose the soil mix of just the composite soil and slurry to be the final barrier material in the wall. This mix design meets the design parameters outlined in the NSF proposal. A construction specification was written for use by the contractor based of these findings.

1. Introduction:

In-ground vertical barriers (i.e. cutoff walls) have been used to control the flow of groundwater and subsurface contaminants for nearly half a century. One of the most commonly used variations of vertical barriers is the soil-bentonite (SB) slurry trench cutoff wall that is named for the type of final barrier materials used (SB) and the construction method (slurry trench). While many of these cutoff walls have been built in the United States and around the world for levee protection and *in-situ* geoenvironmental containment, little research has been done on their short and long-term effectiveness. This is due to reluctance from owners, contractors, designers and regulators to seek and report failures in completed cutoff walls. The

long-term effectiveness of SB vertical barriers is not well understood because laboratory values for permeability, k , obtained from field-mixed backfill specimens may be different than *in-situ* k if the applied stresses in each case are different. For these reasons, a field cutoff wall built for the main purpose of experimentation and research, in a location with long-term accessibility, would be greatly beneficial to furthering the understanding their short and long-term performance.

A. Scope/Objectives:

This above description is the basis for a proposed NSF Grant by Prof. Evans, Prof. Malusis and a Bucknell alumnus, now in the geotechnical contracting industry, Daniel Ruffing. The scope this senior design project represents portions of the first two (of five) proposed project tasks. The first of these tasks is to create a detailed site characterization along the proposed cutoff wall alignment. This will be done by performing site borings at 50-m intervals along the wall alignment using hollow stem drilling with an Acker Soil Scout track-mounted drilling rig that is owned by Bucknell University. Soil cuttings will be brought back the Bucknell Geotechnical Engineering laboratory for testing to determine soil properties such as grain size distribution, Atterberg limits and moisture content. The results of this subsurface investigation will be compared to previous such investigations of which the most recent was done in November 2012. The second task that will be performed by the senior design project group is to generate a SB mix design to be used during construction. This will require extensive laboratory testing and experimentation and is further outlined in the design tasks section.

B. Location:

The proposed site for the SB cutoff wall is located approximately three km east of the Bucknell University campus as shown in Figure 1. The site for the project belongs to a commercial sand/quarry operated by Central Builders Supply (CBS) in Montandon, PA. The site lies adjacent to a wetland known as the Montandon Marsh. The proposed experimental cutoff wall will be built on a section of CBS's property that has been designated as a buffer zone between the permitted mining area and Montandon Marsh. In recent years, CBS has allowed Bucknell faculty and students to access the marsh area for research and other educational activities. As the site is a wetland, the conservancy organization responsible for the protecting this area is the Linn Conservancy. CBS and the Linn Conservancy are fully supportive of this project.

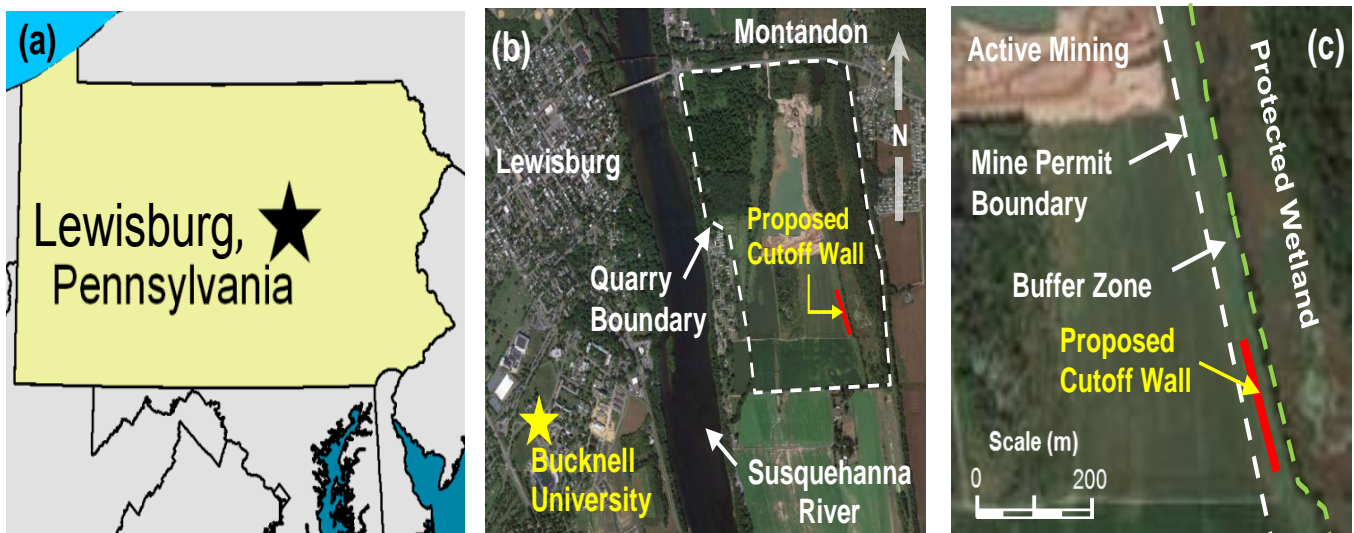


Figure 1. (a) Index map showing the proposed site location in PA; (b) aerial photo showing the relative proximity of the proposed cutoff wall to the Bucknell University campus; (c) aerial photo of the portion of the quarry where the proposed cutoff wall will be located (Evans, Malusis & Jacob, 2014).

C. Background Information:

Prof. Evans has provided the project team with a copy of the NSF Grant proposal that was created by Prof. Malusis, Prof. Jacobs and himself. This document has provided the project team with much of the necessary background information for this project. One example of this is previous site investigations that have been conducted at the proposed site. Figure 2 shows the subsurface profile that was generated after a November 2012 site investigation by students and faculty from Bucknell University. Other background information pertaining to the specifications of the design of the cutoff wall was also taken from the NSF Grant proposal and is outlined in the design tasks section of this proposal.

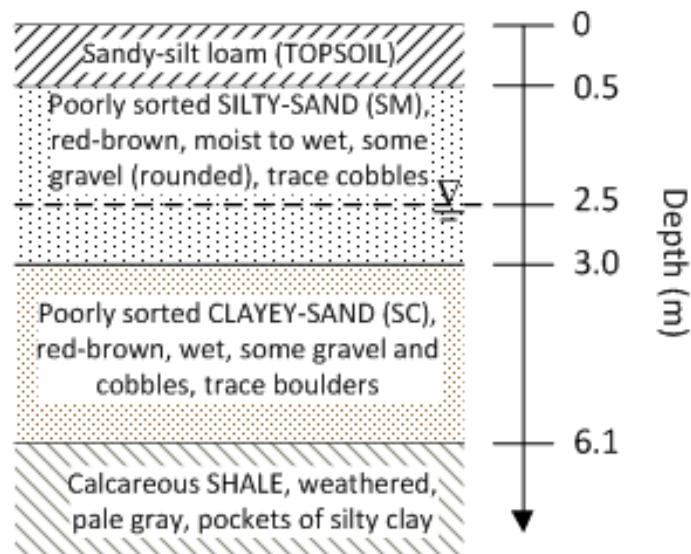


Figure 2. Subsurface profile along cutoff wall alignment from November 2012 site investigation (Evans, Malusis, & Jacob, 2014).

2. Design Tasks:

The design of the slurry wall will be based on data collected from subsurface investigations along with the results of various lab tests, mix designs, and analysis. There are various parameters for the slurry wall that must be met during the design process. The Slurry

wall will be 300 meters in length and 0.6 meters thick. It will reach a depth of seven meters in order to be keyed into the weathered shale aquitard. However, to ensure this depth should be used for the entire length of the wall, borings at 50 meter intervals will be taken to ensure homogeneity along the wall length. From these borings soil samples will be taken in order to determine soil properties via lab testing. These borings will be completed by a hollow stem auger drilling with an Acker Soil Scout track mounted drilling rig.

With the soil samples taken from the borings various test such as grain-size distribution, Atterberg limits, and moisture content tests will be performed to determine the soil properties by layer. A composite soil sample will then be mixed with bentonite in various ratios to determine the most appropriate design for a SB backfill mixture to be used. These mixtures will be performed by mixing approximately 5% Bentonite water slurry with different variations of composite soil. The different mixtures will then be tested for slump and permeability. The target Slump and permeability are $125 \text{ mm} \pm 12.5 \text{ mm}$, and $k \leq 10^{-8} \text{ m/s}$ or less, respectively. The SB mixture will best values of slump and permeability will be chosen for the design. After a composite SB mixture has been created that meets the given parameters, specifications will be written for use by the contractor during the construction of the cutoff wall.

To ensure the design of the slurry wall is maintained GeoSolutions, also the contractor for this project, will be in charge of in-field testing for the slurry properties as well as the SB backfill properties. The properties that will be tested for with the slurry are sounding, viscosity, density, and filtrate loss. The properties that will be tested for the SB backfill are permeability, slump, shear strength, compressibility and homogeneity.

3. Field Tasks:

A. Site Borings:

The borings were done on two consecutive days, January 20th, and 21th. Jim Gutelius was the driller and a Bucknell Civil and Environmental Engineering Department owned Acker drill rig was used. The project team always had at least two team members present during the site borings and all three project team members were able to be on site at some point during the two days of drilling. Throughout the drilling process, boring logs for each hole were completed and can be found in the appendix. In the field testing and visual observation was used to estimate the classification of the soils while drilling. From these site borings auger cuttings were collected for lab testing along with SPT (Standard Proctor Test) and Shelby tube samples. The water table was observed to be 7.5' below the ground surface. The first hole was drilled to a depth of 30 ft. without hitting refusal. This hole yielded two shelly tube samples for use in laboratory testing. The first of these samples was taken in a stiff clay layer from 16.5 feet to 18.5 feet below the ground surface and the second sample was taken from another stiff clay layer 26.5'-28.5' below the ground surface. The second hole was drilled to a depth just under 20 ft., where refusal was determined based on SPT criteria. Based on visual observation there seemed to be more sandy material in the layers closer to the ground surface with a transition to more clayey layers at deeper depths. The samples collected and the boring log data were then compiled to provide a detailed site characterization.

4. Laboratory Tests:

A. Moisture Content:

The determination of the water content is a crucial aspect for the characterization of the soil. Most natural soils that are sandy and gravelly have water contents that are approximately

15-20% . The natural sand grained (silty or clayey) soils have approximately (50-80%) can be found. The soil samples from the borings were brought in the Bucknell Geotechnical Engineering Laboratory and were immediately tested for the water content. The weight of the empty aluminum foil pans were measured and recorded. Then they were again measured with the soil in samples from every depth of the auger cuttings from the first boring. They were then put in the oven for 24 hours and then the weights of the pan along with the soil were measured and recorded again. The water content ranged from 10- 30% for the soil samples from the first boring. Similar procedure was followed for the second boring. The moisture content was taken for both auger cuttings and SPT samples for both the borings.

B. Grain Size Distribution Test:

Similar to the water content, grain size distribution test is essential in order to classify the soil for the site. Sieve analysis method was performed in order to determine the grain size distribution of the soils. This was done on all the representative soil samples that were collected from the borings on the site from various depths. The sieves used for the analysis were sieve numbers 4, 10, 20 ,40, 60, 100 and 200. A balance that was sensitive to 0.01 g was also used. The mortars and rubber- tipped pestles were also used to crush the soil samples. Firstly, these representative soil samples were put in the oven for more than 24 hours (for 2 days approximately). The auger samples from the first boring and the SPT samples from the second boring were taken and approximately 500g were used for the grain size distribution test. The mass of the soil was measured and recorded. The stack of sieves was prepared and their masses were measured and recorded before the soil was put through them. The stack was shaken for a good 10 minutes by hand and then was placed again in the shaker for 15 minutes. After that the mass of the soil and the pan was measured individually and recorded. If a considerable amount

of soil was retained on the pan, after passing through the No. 200 sieve the soil was collected separately for the hydrometer analysis. Figure 3 shows a representative grain size distribution graph.

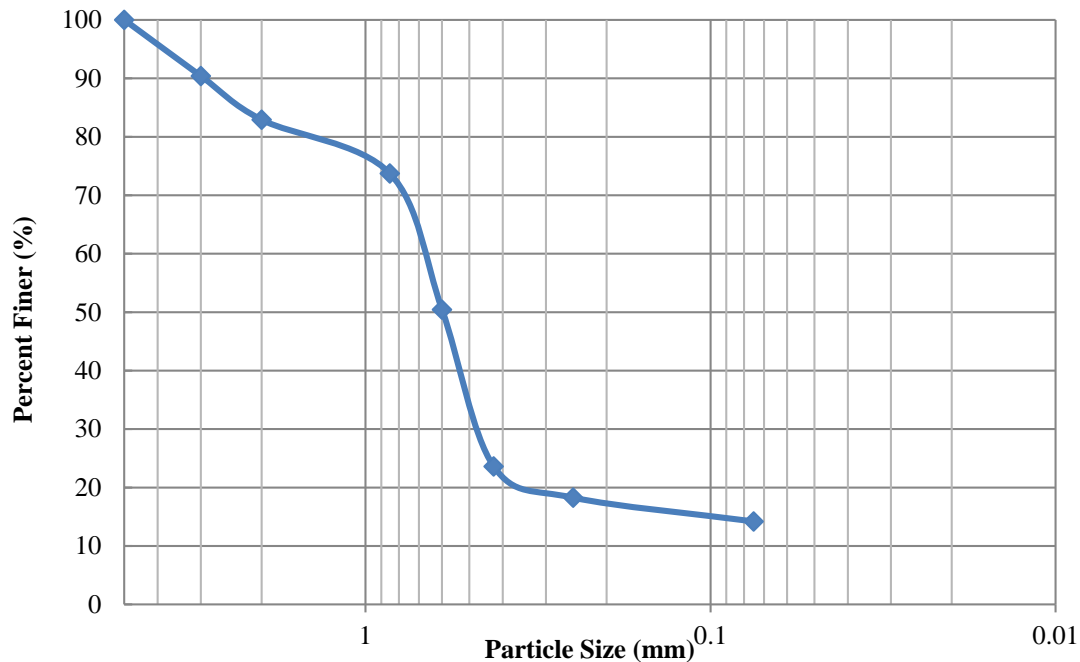


Figure 3. Plot representing the grain size distribution for the soil sample retrieved between 19-20.5 feet from Boring 2.

C. Atterberg Limit Test:

This test was performed in order to find the Liquid Limit and Plastic Limit test. The first boring had enough sample to conduct the atterberg limit test, unlike the second boring. Therefore the atterberg limit test was conducted only on the first boring soil. For the Liquid Limit Test, the soil samples were oven dried and the soil retrieved after passing through No. 40 sieve was used for the test. 250g of the representative soil sample was collected and put into the evaporating dish. A sample representative graph is shown in Figure 4. Then, water was added continuously to make the soil like “paste”. It took more water than expected to make the soil really uniformly moist and smooth. After that the soil sample was put in the Casagrande cup, until the maximum depth is approximately 8mm. Then the soil sample was cut in between. The device was cranked

at the rate of 2 revolutions per minute and the number of counts for it to reach the closure with a possible 1/2” remaining were recorded.

For the Plastic Limit test, approximately 20 grams of the soil samples were used from each depth and water was added to them to make them smoother. The soil sample was rolled until the diameter reached 3.0 mm and when it crumbles, take the sample and put in in the oven and the water content was measured.

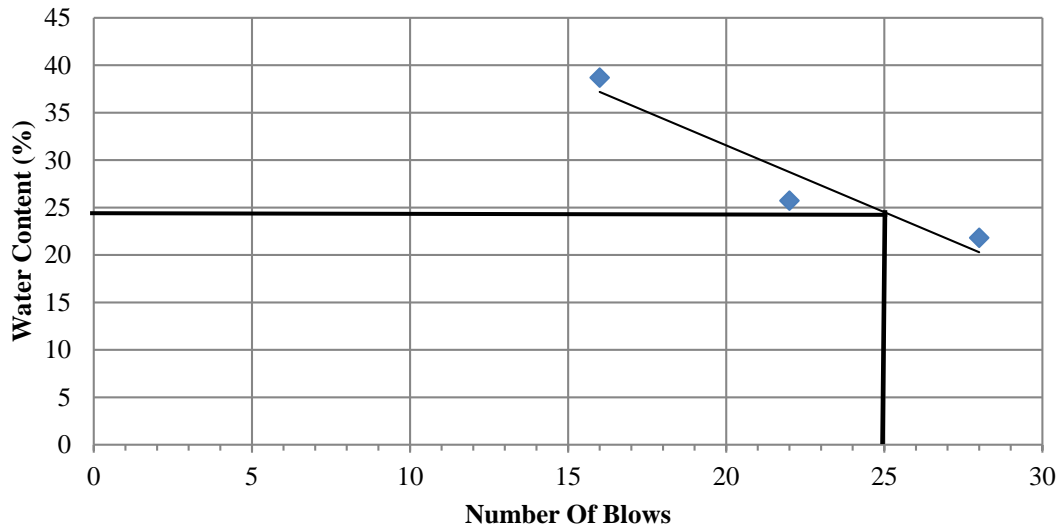


Figure 4. Plot representing the liquid Limit test for the soil sample retrieved between 5- 7.5 feet from Boring 1.

D. Soil Profile:

After conducting the soil classification tests, the soil profile was made in order to characterize the site. This was an important step for the project in order to know the different soil types that exist on the site and conduct a detailed site characterization. Therefore, after conducting the grain size distribution tests, hydrometer tests and the Atterberg limit tests, the soil profiles in Figure 3 were determined. The soil profile from Boring 1 showed that up to the depth

of 8 feet below the ground, there was mostly silty sand (SM) present with the moisture content of 13.10%. Similarly for the soil profile obtained for Boring 2, it is seen that for the depth of approximately 8 feet below the ground, it consisted of mostly silty sand (SM) as well which consisted of moisture content of 11.10%. For both the soil profiles, the layer underneath the silty sand, consisted of more clay particles. For the soil profile in boring 1 consisted of well graded clayey sand (SC) , which had the moisture content of 14.98% and the soil profile for boring 2 consisted of the same soil type with a slightly different moisture content of 7.10%. This soil profile showed that there was more clay particles deeper into the ground. This was expected because the site location is very close to the Susquehanna River which consists of much alluvial deposit. The soil classification tests conducted after the borings have verified that there are primarily silt sand on site along with little gravel and cobbles that were found. This is a detailed characterization of the site that needed to be done in order to conduct the design portion of the wall and come up with the mix designs for the wall. However, these boring conducted are at separate distance along the alignment of the proposed wall, therefore engineering judgment was used in order to predict the soil types between these borings.

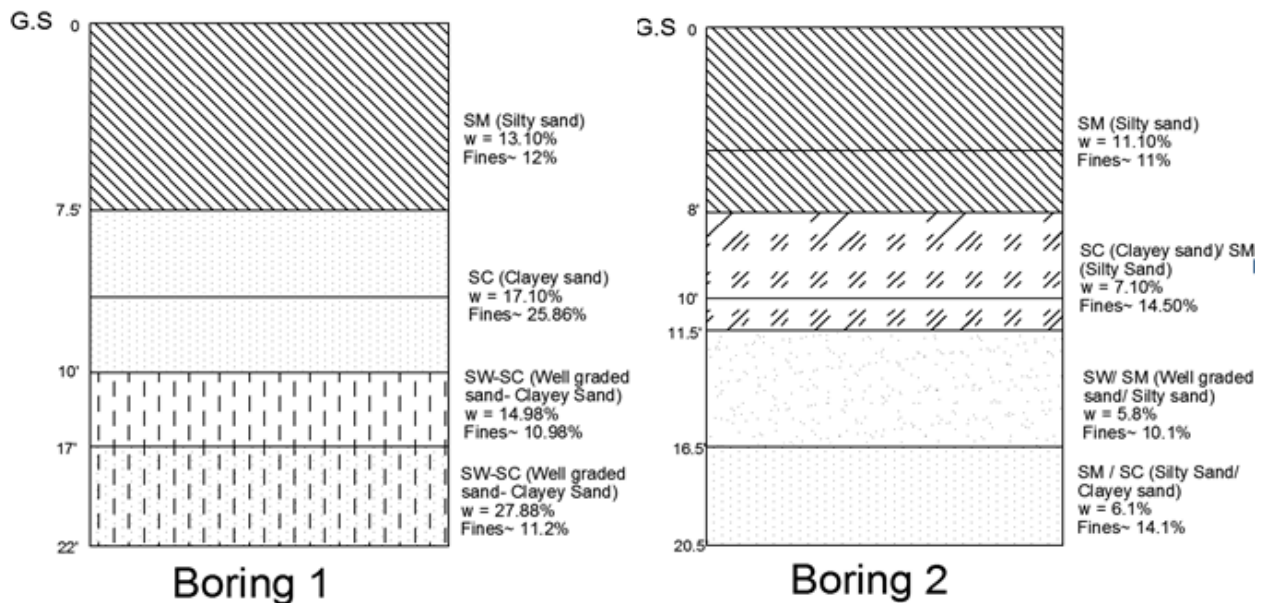


Figure 5. The two soil profiles for Boring 1 and Boring 2.

E. Consolidation Test:

Samples from the shelly tube retrieved in the first site boring at 16.5'-18.5' were used for consolidation tests. The consolidation ring was taken and its height and mass was measured and recorded. Three approximately 3" samples were cut from the shelly tube and was squeezed into the consolidation ring, the remaining parts of the soil were cut out of the using a trimmer. The mass of the specimen and the ring were measured together and recorded. Then the porous stones were placed on the top and bottom of the ring and were lowered in the water beaker. It was ensured that there was no movement of the ring and the porous stones were adjusted carefully to the loading device. Load increments of 1/2 tsf, 1 tsf, 2 tsf, 4 tsf, 8 tsf and 16 tsf were used and measurements were taken on the dial gage for determination of the time rate of consolidation. This test showed slightly over-consolidated clay with an OCR of 3.0 and a past pressure of 2.5 tsf. Figure 6 shows the resulting consolidation curve.

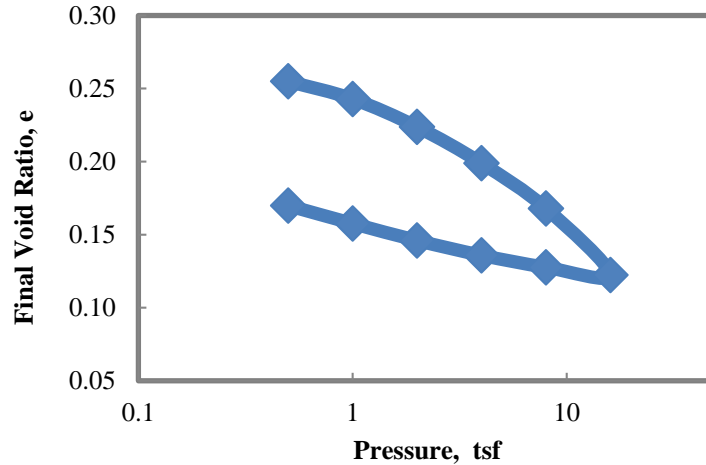


Figure 6. Consolidation curve for clay at 17.5' below the surface at boring 1.

F. Triaxial Shear Stress Test:

One of the very first tests performed on our soil samples was a Triaxial Isotropic Consolidated Undrained test, CIU. This was done on the second Shelby tube sample at a depth of 26.5 ft to 28.5 ft. The Shelby tube had full recovery from the site and therefore provided three very nice 5.75 inch samples to be tested. To run these test they were set up on a pressure inducing board Once set up they were then consolidated each with a different effective stress, one with 10 psi, another with 15 psi, and another with 25 psi. Due to this varying effective stress three different effective stress circles will be provided. This distribution of different effective stresses will be used to geometrically calculate the shear strength of the soil and determine the cohesion, c' , of the soil. Once the samples are consolidated they are ready to be placed into the GEOTAC machine which applies an axial stress to the sample, steadily increasing at a constant strain rate until the strain in the reaches 15% or the soil fails in shear. These data points are

acquired automatically and are logged in a data file which is then translated into an excel file where the data needed to perform the calculations can be found. The setup of this test is shown in Figure 7 along with examples of how the soils tested failed in shear.

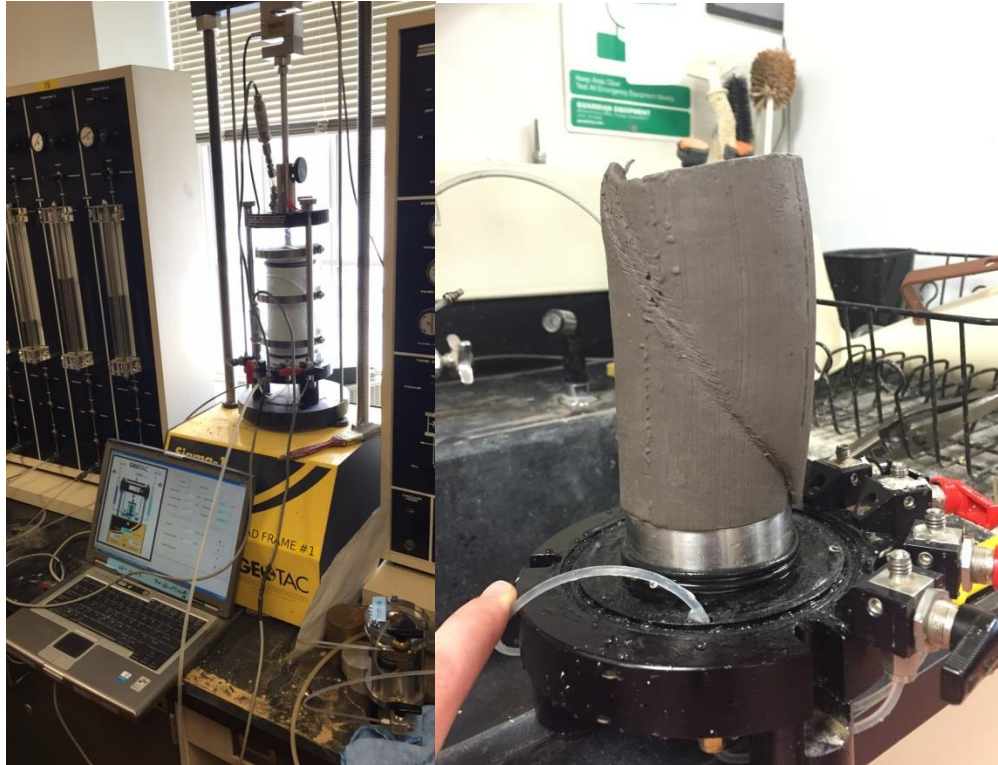


Figure 7. Set-up of triaxial shear strength test (left) and sample after failure in the shear strength test (right).

The Clay material that was found at this depth was a great sample and provided very good results. However, one of the samples was determined to be invalid. The sample with an effective stress of 25 psi “failed” at a lower effective stress than the sample with 15 psi effective stress resulting in a smaller effective stress circle. It was determined to be invalid because this shouldn’t happen. As the effective stress increases the friction forces resisting the shear will have a higher capacity. This result could be due to a number of things, something was either wrong with the setup of the cell or actually on the GEOTAC, there was a human error, or the GEOTAC machine malfunctioned. Even though the 15 psi sample failed the results were still very good

since the 10 psi sample and 15 psi sample yielded what would be expected. The 25 psi sample in a perfect world would have fell right of the 15 psi sample only reassuring the result is accurate. However, as shown in Figure 8, the two samples that did work provided enough data to yield $\phi=30^\circ$.

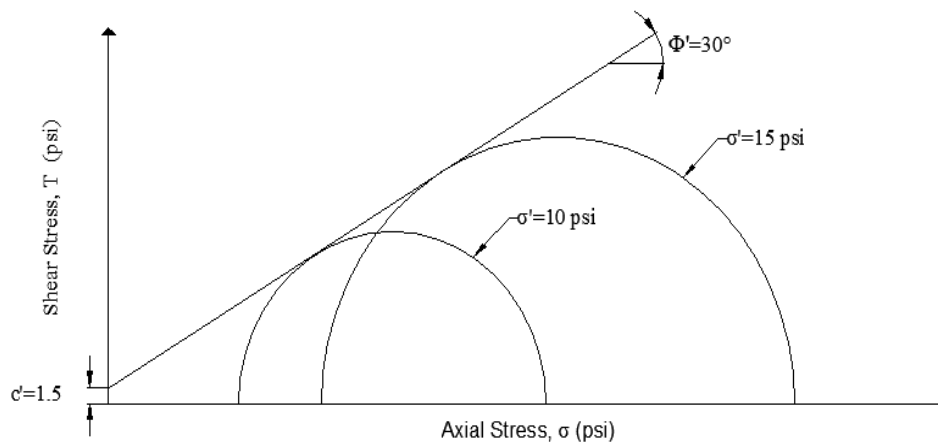


Figure 8. Mohr's circles from triaxial shear strength tests of clay 26.5'-28.5' from Boring 1.

Another important value extracted from these results is the c' value, which is 1.5 psi. This value means that the clay is slightly over consolidated which is consistent with our consolidation test results which yielded an OCR value of 3.0, a relatively low OCR. These results are used in the design calculations later on in the project for trench stability and vertical stress distribution respectively.

Two more triaxial CIU tests performed on the Shelby tube sample from 16.5'-18.5' after the perm cell tests were run on them in order to determine the permeability of this specific layer. These test yielded a $\phi=29^\circ$ and a $c'=0.4545$. These make sense based on the data from the first

test we ran and since this sample is from a shallower depth it is expected that the c' is smaller.

Figure 9 shows these results.

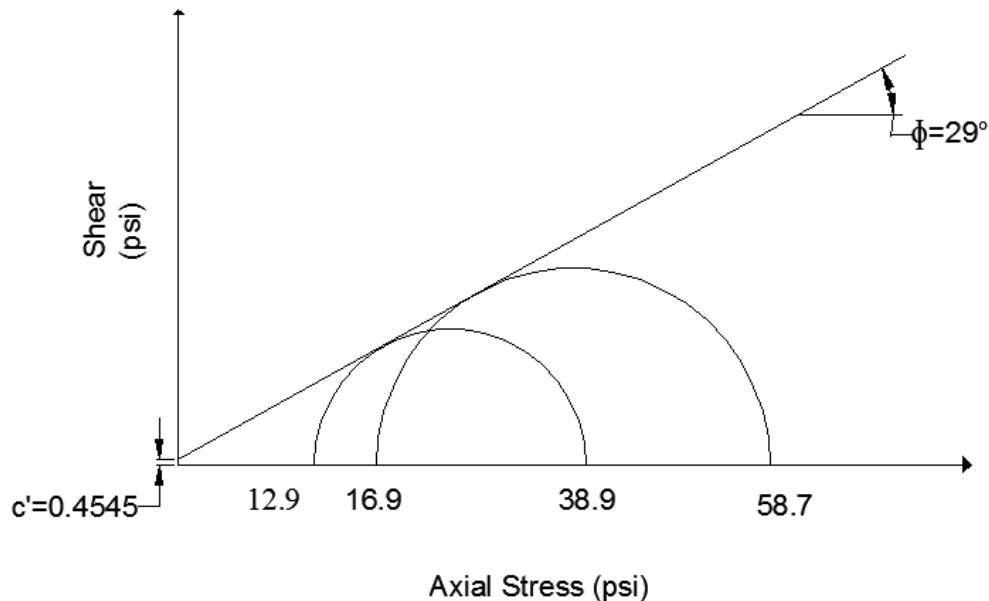


Figure 9. Mohr's circles from triaxial shear strength tests of clay 16.5'-18.5' from Boring 1.

G. Triaxial Flex Wall Permeability Test:

The Triaxial Flex Wall Permeability test is a sophisticated way of determining the soil hydraulic conductivity, or permeability. It is the same set up as the triaxial tests however the soils do not have an axial stress applied until they are failed due to shear. These tests are set up in a way which applies an effective stress of 50 psi on the soil but also applies a head pressure of 45 psi and a tail pressure of 35 psi therefore producing a 10 psi gradient within the soil sample. After these pressures have been applied readings were taken on the cell, head, and tail barometers. These measurements show the movement of water through the sample which will later be used to calculate the permeability through a correlation to volume since the increments

on the barometers are not exactly 1 cm³. For the tests that were run, two 5.75 inch samples were used from the shelby tube sample at 16.5' to 18.5' in our soil column. The results of this test are in Figure 10. As shown, the permeability rate increases in imperviousness as time increases until the sample reaches equilibrium where a constant permeability rate can be observed which in this case $k=10^{-7}$ cm³/s. This is a very small permeability and often a target range for most cutoff walls. This is indicative of a material that could be keyed into during construction of the wall. This value also shows that this material will make a great cutoff wall and this type of construction is very plausible or applicable for this sight at Montandon Marsh.

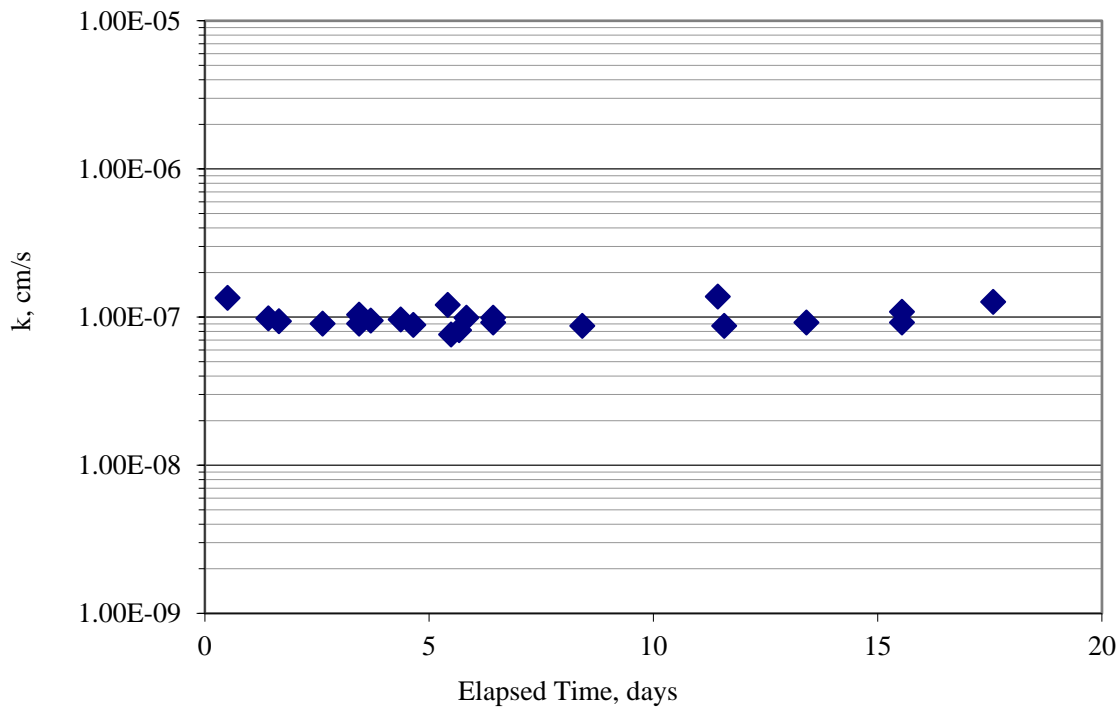


Figure 10. Permeability of Shelby tube sample at between 16.5' and 18.5' from Boring 1.

5. Design Tasks:

A. Mix Design Calculations:

'Target Grain Size' calculation was done in order to determine the target grain size distribution of the soil composite mix that gives a good representation of the sample collected. In

order to do so, the percent passing for each sieve was determined and which was then averaged and multiplied by the percentage of each soil layer. Finally, a percent passing was calculated for each of the sieve by the average percent volume of the sample, which was a proper representation of the soil sample. Similarly, the moisture content was also calculated using percentage depth for each of the soil layer which was multiplied to the average soil moisture content for each depth. This gave the target moisture content to be reached.

In order to reach the target mix design, certain proportions of soil from each depth were taken and the sieve analysis was performed. After three trials of mixing the soil proportions of different depths, the target grain size distribution was reached as shown in Table 1. The target water content was also reached. This was checked calculating the water content using the equation which was equal to the target water content. The grain size distribution shows that the target was reached as shown in Figure 11.

The slurry was then made by mixing 5% Bentonite by the weight of dry mass and 95% water. After the slurry was made, it was mixed with the soil sample that was created that had the target grain size distribution. After that, the sample was used to take a representative sample to take the moisture content. Then, the required amount of sample was taken in order to perform the consolidation and permeability tests. Three other samples were made which consisted of 1% Dry Bentonite and Slurry, 2% Dry Bentonite and Slurry and 3% Dry Bentonite and slurry by adding 1% Bentonite to the dry mass. These four samples were used to conduct the consolidation and permeability tests.

Table 1. Calculation representing the target grain size distribution to create the composite mix to represent the soil profile.

Sieve Number	Percent Passing for each Depth(ft)						Composite mix
	0-7.5	7.5-10	10-17	17-20	20-25	25-30	
4	79.6	80.0	80.7	80.7	80.2	99.3	80.1
10	55.1	56.2	75.9	75.6	75.9	95.6	69.2
20	40.3	41.5	65.0	64.4	61.3	70.5	54.8
40	29.6	30.8	39.4	39.0	47.0	65.9	39.6
60	18.9	20.2	23.8	24.0	28.8	51.5	26.0
100	12.6	14.0	15.7	16.3	19.7	26.9	16.5
200	11.0	11.0	9.7	10.7	10.5	7.5	9.7
Percent Depth	0.3	0.1	0.2	0.1	0.2	0.1	
Water content	13.6	20.0	15.0	27.9	26.6	20.1	18.5

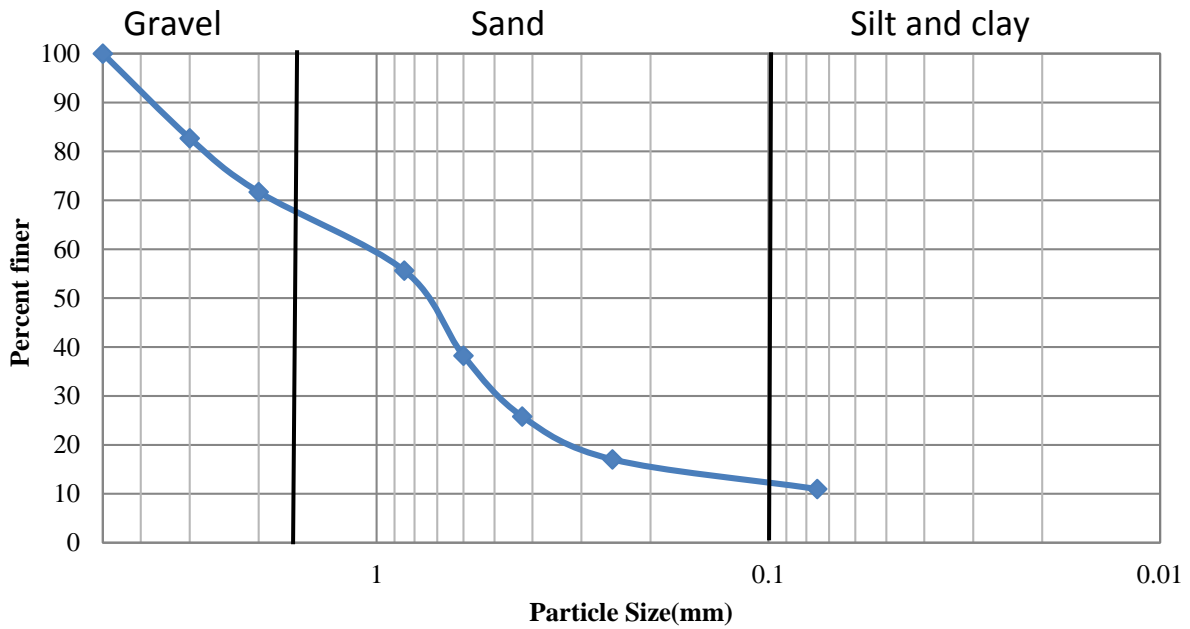


Figure 11. The grain size distribution plot for the target composite soil mixture.

B. Marsh Test:

The marsh cone was used to measure the viscosity of the slurry and the density was also measured as shown in **Figure**. The test was conducted by putting the slurry in the funnel through the screen and then stopping the slurry in the cone using a finger at the end of the funnel. The slurry was then poured into the cup and the time was measured to reach the height of 1qt on the cup. The slurry created by the project team had an average marsh viscosity time of 34.32 seconds over three trials which falls in the acceptable range of 32-40 seconds specified in the NSF Proposal (Evans, Malusis, Jacob, 2013).

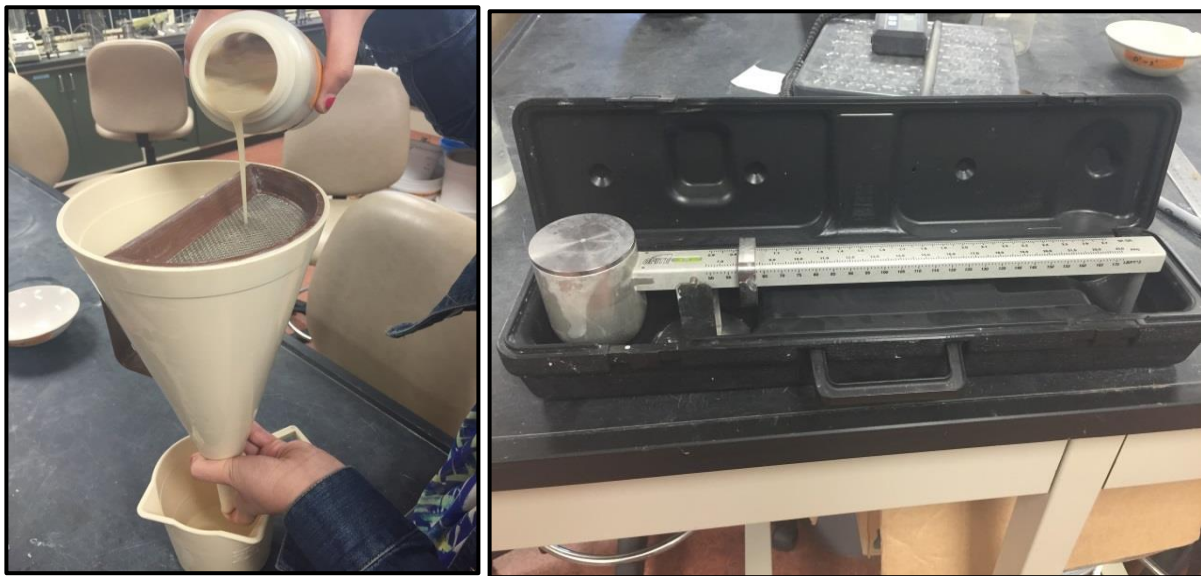


Figure 12. Marsh viscosity test (left) slurry density calculation (right).

C. Slump Test:

The slump test was conducted in order for the sample to reach a certain slump design of 1- 2 inches in the miniature slump cone (Malusis et al, 2008). After preparing the slurry and mixing it with the composite mix sample prepared, the slump test was conducted. The slump for

the sample was just over one inch as shown in Figure 12, which was within the design specifications.



Figure 12. The measurement of slump of the slurry and soil sample.

D. Consolidation and Permeability Test:

After finding the target grain size distribution and preparing the composite mix of soil with the 1% bentonite, 2% bentonite and 3% bentonite with slurry and fourth sample with just the slurry itself, a combined permeability and consolidation test was conducted on the sample. The sample with the target grain size distribution was weighed and initially just the slurry (95% bentonite and 5% water) was placed and then, the sample was retrieved for the test. The moisture content was measured for the sample as soon as it was prepared. Then, the sample was placed on an O-ring, which was fitted with a 2.5" filter paper in the ring. The diameter was recorded to be 2.50 inches with the depth of the sample to be 1 inch. The sample was filled into the o-ring with less air as possible and covered with another filter paper on the top. Then the saturated brown plate was placed on top to cover the sample. The setup was cleaned and checked for any leakage after and then was connected to the permeameter with a dial gauge. The permeameter was assembled and all the seals were tightened. There was a pipe connecting the burette to the sample which was used to record the difference in the water level with time. After every increment of

loads added to the sample, the initial time was recorded after a few hours of the addition of load. The load increments were $\frac{1}{4}$ tsf, $\frac{1}{2}$ tsf, 1 tsf, 2 tsf, 4 tsf and 8 tsf. The height of the water level in the burette was measured and recorded along with the time, for all the loads added to the sample. Along with the permeability, the consolidation was also measured from the dial gauge that was connected to the sample. With every load increment the dial gauge readings were taken immediately for certain time intervals.

The same procedure was followed for the other samples with the 1%, 2% and 3% bentonite mixes. In order to prepare the different bentonite mixes, the respective percent of bentonite by the mass was added to the composite mix of soil and the same procedure was followed accordingly.

E. Consolidation Data Analysis:

After the consolidation tests were finished, the collected data was organized and analyzed. It became evident that the amount of dry bentonite in a sample directly impacted the results of the consolidation tests. Figure 13 shows the consolidation curves for each of the four soil mix design samples. It can be seen that while the initial void ratio was similar for all four samples, the void ratio decreased more drastically with increasing dry bentonite. The sample without any dry bentonite and the sample with 1% dry bentonite followed similar curves but there was a significant difference between them and the other two samples. The sample without any dry bentonite followed a typical consolidation curve as it was concave down for the first part of it and then had a near-linear recompression curve when the weight was systematically reduced. This typical curve form was not observed in the other three samples though. Each of the three samples with dry bentonite has a concave up first part of its curve with increasing concavity pairing with increasing added dry bentonite. This result was not expected but can most

likely be explained due to the balance between the mechanical pressure supplied by the consolidation apparatus and the swelling pressure due to the added bentonite. The sharp decrease in void ratio is due to the swelling in the clay and not due to the mechanical pressure at low stresses and then at higher mechanical pressures this causes the decrease in void ratio, thus resulting in the opposite concavity of the early part of the curve. This phenomenon was likely evident in these tests because the project team moved quickly between creating the sample mixes and starting the consolidation tests, thus not giving the bentonite time to swell prior to the test beginning.

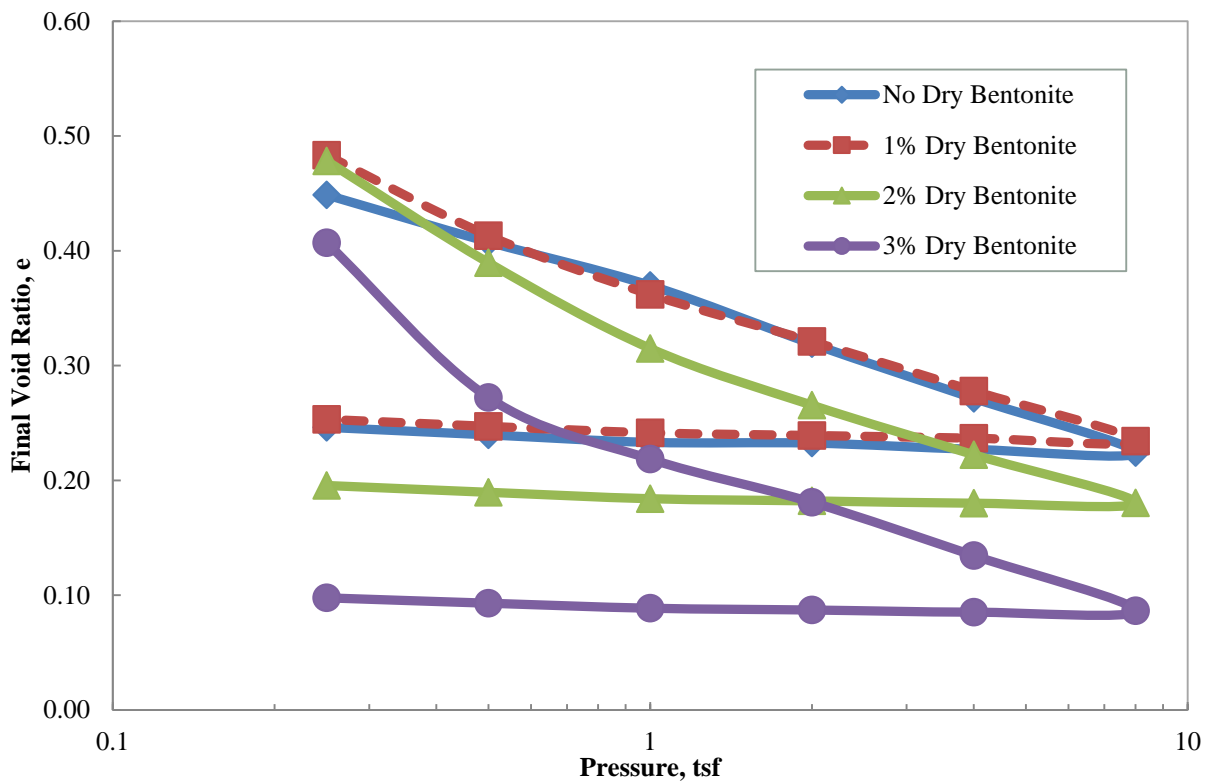


Figure 13. Final void ratio as a function of pressure (tsf) for the four composite soil mix designs.

The coefficient of compressibility, c_v , is one of the important terms that was able to be calculated based on the results of the consolidation tests. A c_v value was calculated for each soil

sample at each loading pressure and these are shown in Figure 14. These values show how much area of soil is compressed per unit time and it was expected that the samples with added dry bentonite would display lower compressibility terms. Decreased compressibility is a desirable trait of a cutoff wall because it means the wall is set much quicker and the wall properties become more predictable. This pattern was found in the data from the consolidation tests. As the dry bentonite increased the range of c_v values decreased such that the soil-slurry mix's curve follows a power function regression curve while the 3% dry bentonite distribution is much closer to linear. There is a less significant difference in the compressibility of the four mix designs at lower pressures as there is at higher pressures which was also expected and compression is induced by pressure.

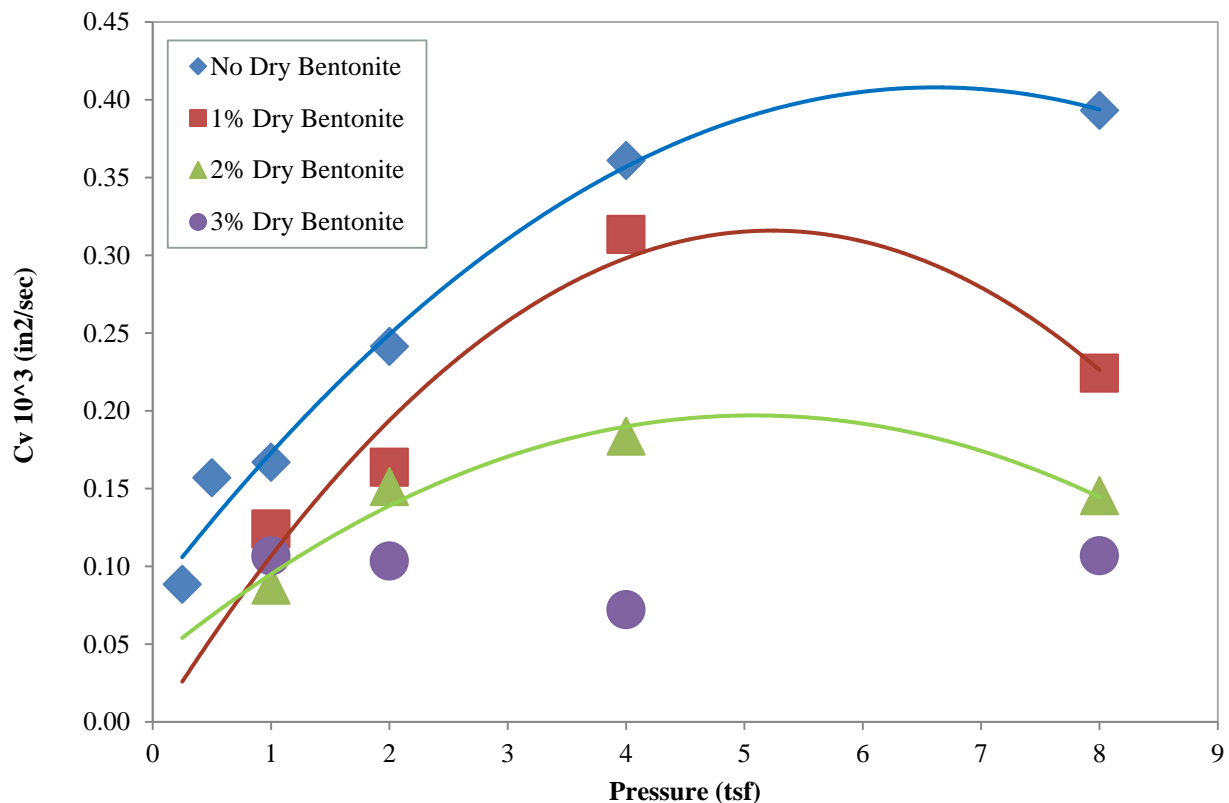


Figure 14. C_v values (in^2/sec) of the four mix designs as a function of pressure (tsf).

F. Permeability Data Analysis:

After collecting the data for the permeability test, the analysis showed that the value of k (cm/sec) decreased with the increasing percent of bentonite. The test yielded reliable data and showed the expected trends. Figure 15 shows the trend of permeability decreasing as the amount of added dry bentonite increased. This was expected because an increase in the percentage of bentonite in the soil sample will allow less water to flow through it because the bentonite will have fewer voids due to swelling and therefore will allow less what to flow through. This trend can be seen at regardless of what pressure the soil sample was under. Similarly, when the pressure was increased the permeability decreased. This occurred for all the slurry and the bentonite mixes. This was also expected because when the pressure is increased the soil becomes more compact which makes it harder for water to flow through it.

All the mix designs satisfied the criteria of 10^{-6} cm/ s which was the design constraint chosen. This value was chosen because it will make sure the wall is representative of other soil-bentonite cutoff walls, therefore ensuring that the research conducted on the wall can be generalized for industry use. The composite soil mix with just the slurry showed that the k value ranged from 10^{-6} cm/ s to 10^{-7} cm/s which is a good range and close to the realistic value which would make it easier to compare with the other cutoff walls. This range matched closely to the design specification range which required the value of k to be less than or equal to 10^{-6} cm/s.

Due to this result, the soil and slurry mix without any added dry bentonite was selected as the design mixture. Making this choice also increases the economic and time efficiency of the wall. Dry bentonite would be a relatively expensive addition to the cost of the wall so by choosing not to use it there is a significant drop in price. Choosing the soil and slurry mix also means future research testing will be able to be completed faster as at almost every pressure the soil and slurry mix had the largest permeability. Figure 15 shows that for the 3% Bentonite, it

takes approximately 10^{-8} cm/s at 4 tsf whereas it takes approximately 10^{-7} cm/s for the slurry only mix. Therefore, it would take 10 times as long to run a permeability test on the 3% bentonite mixture than it would on the soil and slurry mix.

This also confirms that the excavated soil can be used to create the final barrier material because this is what was used to conduct these tests and the results meet the given parameters. If the soil on site did not sufficiently meet the design constraints then soil would have had to have been brought in from off site to mix with the excavated soil or the contractor would have had to separate out certain grain sizes before making the backfill mix. Both of these options would have been more expensive and more time consuming so it is beneficial that they do not need to be considered.

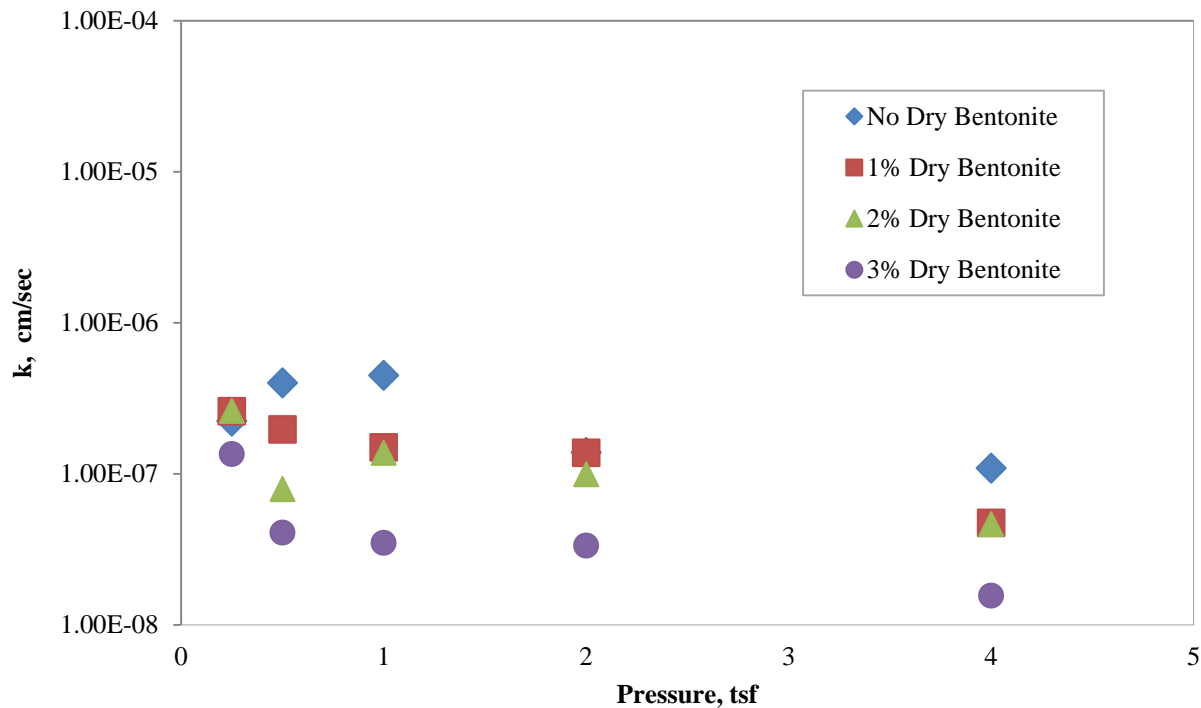


Figure 15. Permeability (cm/sec) as a function of pressure (tsf) for all four soil mix designs.

H. Trench Stability and Calculations

Trench Stability calculations were performed in order to ensure the safety of the design and offer specifications for the contractor. Figure 16 shows the basic layout of the trench during construction and the variables in their respective places.

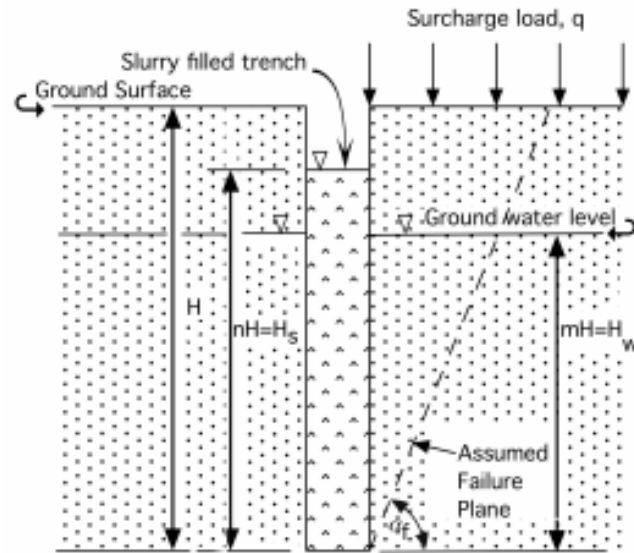


Figure 16. Visual representation of variables used to calculate trench stability (Evans and Malusis, 2013).

These calculations included multiple variables which can be found in the *Equations 1* and 2.

$$B = \frac{2q + H[(1 - m^2)\gamma_m + m^2\gamma']}{H(n^2\gamma_s - m\gamma_w)} \quad (1)$$

$$F = \frac{2\sqrt{B} \tan(\phi)}{B - 1} \quad (2)$$

Where B is the dimensionless stability index, F is the factory of safety, m is the ratio between height of the water table, H_w , and height of the wall, H , n is the ratio between height of the slurry, H_s , in the trench and the height of the wall. In order for these calculations to be done a

few assumptions had to be made. One assumption that was made was the value of Φ . Although this value was measured for the clay through use of the triaxial tests, we determined that it was acceptable to assume this as the Φ for the entire column to be 30, noting that it will only increase in strength when the soil becomes more granular. This is a very conservative assumption.

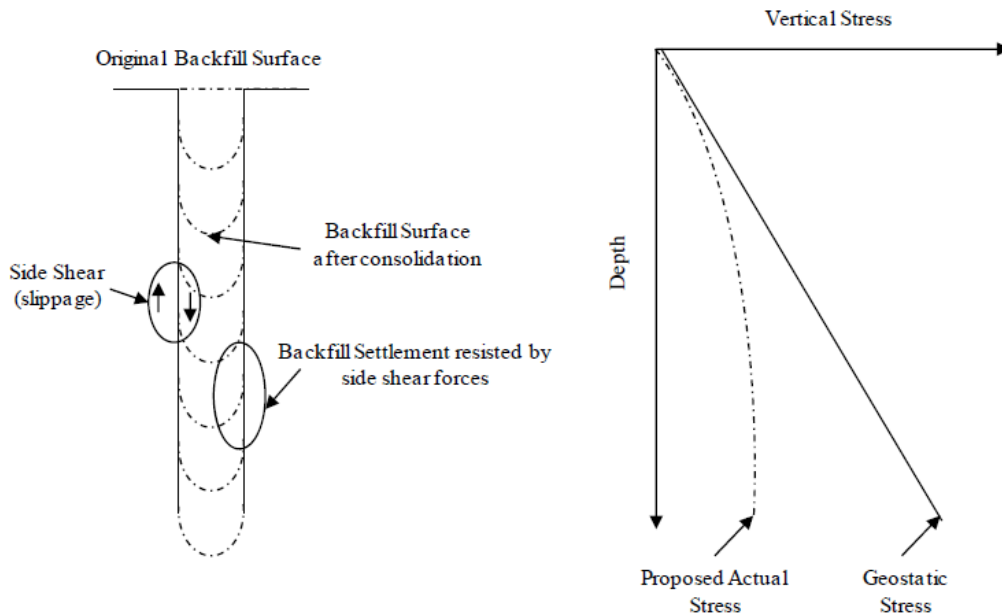
Another important assumption we made is in regards to the various unit weights that were used in calculations. For the moist unit weight of the soil above the water table we used the SPT Empirical relationship values where the N count was used to estimate the unit weight (Das, 1985). This was also done for the saturated unit weight of the soil below the water table. The N count for those soils were assumed to be the same as that found in the clay layer again noting that this is a conservative assumption since sand and gravel will only increase the unit weight.

The calculations were performed in excel so that we could iteratively arrive at a design height of slurry in the trench. The following tables show the data from our final design height. The calculations yielded a Factor of Safety of 1.05. It is important to note that it is typical for the factor of safety to be below one for low density slurries, around 1.05 g/cm^3 . This value however is not what we used in our calculation. We assumed a higher density of 1.35 g/cm^3 , or 84.24 pcf , in order to account for the mixing that will occur in the actual construction of the trench. Using these assumptions and the data we collected we concluded that the height of the slurry must be maintained at 29 feet or higher throughout the entire construction process.

I. Vertical Stress Distribution Analysis and Calculations:

The vertical stress that the SB backfill will experience is a critical factor in design. The maximum stress experienced by the wall will be used in conjunction with the results from the consolidation and falling head permeability tests to determine the design permeability and c_v

value of the wall. It is important to note that the same assumptions used regarding the soil properties are the same for this calculation as those in the trench stability calculations. Figure 17 shows the comparison between the natural geostatic vertical stress distribution and the actual *in-situ* vertical stress distribution. Figure 17 also shows the equation used to calculate the vertical stress at a given depth. The difference in the expected and observed stress is due to the side shear forces resisting settlement which ultimately results in a mitigation effect on the vertical stress experienced by the backfill.



$$\sigma'_v = \frac{\left(\frac{B}{2}\right)\left(\gamma'_b - \frac{2c_b}{B}\right)}{k_{ob} \tan(\phi'_b)} \left\{ 1 - \exp\left[-2k_{ob}\left(\frac{z}{B}\right)\tan(\phi'_b)\right] \right\}$$

Figure 17. State of vertical stress distribution (top) and equation for vertical effective stress at a given depth (bottom) (Ruffing, Evans and Malusis, 2010).

This equation takes into account the unit weights of the soils, and shear strength as depth increases. In Figure 18 the variables are defined and shown in the respective places on a sample cross section. As stated above this is a vital calculation with regards to our design, providing us with the pressure that we will use to pick out the corresponding permeability rate and c_v value. In summary due to the nature of the soil backfill the settlement experienced within the trench creates shear forces that counteract the pure geostatic stress.

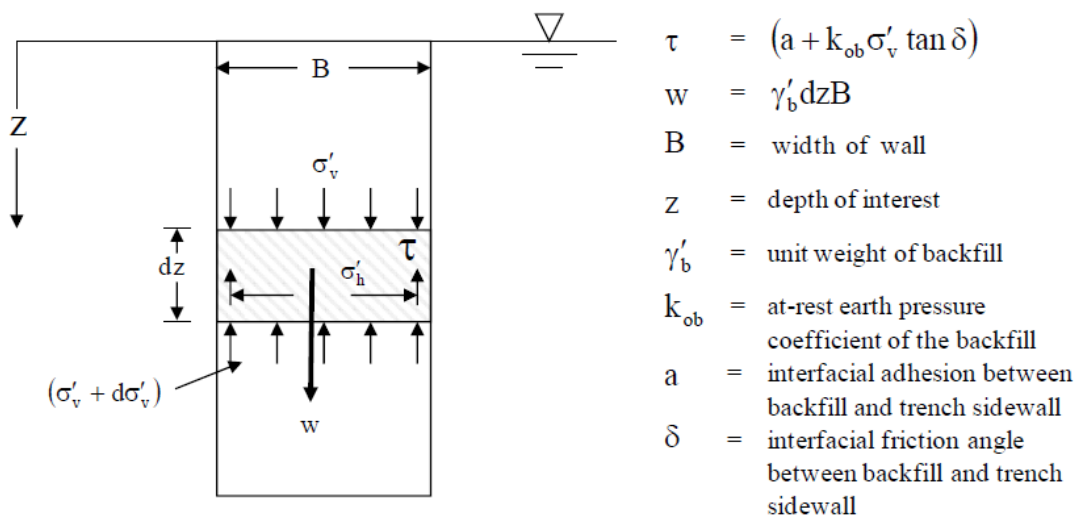


Figure 18. Factors affecting the vertical stress in a vertical cutoff wall (Ruffing, Evans and Malusis, 2010).

6. Schedule and Challenges:

At the end of the 2014 Fall semester the project team created a proposed schedule of work to be done during the 2015 Spring semester. This schedule was updated as necessary during the Spring semester and the latest version is shown in Table 2. Week one is designated as starting on Wednesday January 14, 2015 and the schedule runs through the end of the 2015 Spring semester. Extra time was allotted for the tasks that the project team foresaw potential challenges with. The project team was able to stay on this schedule without any significant challenges throughout the course of this project. This was in large part because the field drilling

portion of the project was able to be completed early in the semester despite wintry weather. This allowed the laboratory work to begin on schedule and other work to be completed when expected. Some of the laboratory tests such as the consolidation tests were time sensitive and time intensive which required advanced planning by the project team to make sure these tests were progressing as scheduled.

Table 2. Proposed schedule and work breakdown.

Task	Work Breakdown	Time (Week)															
		Pre-Semester	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
Schedule Field Work		x															
Perform Field Work	Site Borings		x	x	x												
	Collection of Cuttings		x	x	x												
Laboratory Testing of Boring Samples	Grain Size Distribution (Sieve and Hydrometer)				x	x	x										
	Atterberg Limits				x	x	x										
	Moisture Content				x	x	x										
	Consolidation					x	x	x	x								
	Shear Strength					x	x	x	x								
	Permeability					x	x	x	x								
Calculate Potential Mix Designs										x							
Laboratory Testing of Mix Designs	Slump									x	x						
	Consolidation									x	x	x	x				
	Shear Strength									x	x	x	x				
	Permeability									x	x	x	x				
Examine Test Results	Rank Alternatives													x			
	Choose Best Alternative													x	x		
Write Specifications															x	x	x
Write Report						x	x	x	x	x	x	x	x	x	x	x	x
Presentation	Create													x	x	x	
	Practice															x	x
	Final Presentation																x

7. Final Design Summary

After completing the detailed site investigation and the mix design phases of the project the project team completed a final design for the soil bentonite slurry trench cutoff wall. This

design includes three sections: configuration, slurry mix design, and backfill mix design. This design is prefaced by the recommendation for further site investigation along the wall alignment as the two borings that were taken provided some different information in terms of the depth to bedrock and thickness of certain soil layers. A more expansive site investigation could garner further information to create a more reliable subsurface profile. The configuration design of the wall is two feet wide and 30 feet wide. This width should be suitable to obtain strong research results while being economical in terms of the amount of soil that is excavated and the equipment necessary for the contractor to perform the work. This design depth will allow for the wall to key into the thick clay layer which was found near 26.5' below the ground surface. The design depth may need to be adjusted based on the further site investigation as bedrock has been found at three different depths in the three most recent borings at the site (the 30 feet design depth is based on the first boring the project team completed).

A slurry mix of 95% water and 5% bentonite was determined to produce the required values for viscosity and density and thus can be used for the wall. A calculation of trench stability during construction yielded that the slurry level would need to be maintained at 29 feet.

Based on the vertical stress distribution calculation, less than 0.25 tsf is expected to be the effective stress on the soil. This, along with the permeability results, led the project team to select the slurry-soil mix design without added dry bentonite as the final backfill material. With this decision made, the project team then went back to the test results to determine the design permeability will be $\sim 5 \times 10^{-7}$ and based on the design c_v value the expected t_{90} or time to 90% consolidation is 16 days. The expected moisture content and unit weight of the backfill are designed as 18% and 125 pcf respectively. These *in-situ* soil parameters will also need to be

reevaluated during final design and construction of the cutoff wall as they are heavily dependent on the field conditions.

The design specifications for construction are included in the appendix.

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Further Discussion:

Discussion of the sustainability principles considered in the design project:

Soil Bentonite Cutoff walls are generally known to be very sustainable. The raw materials that are used in this wall are naturally occurring soil and slurry which are sustainable compared to other materials used in different walls such as sheet pile and tangent walls. Most of these other walls use materials such as cement and steel which are comparatively less sustainable materials.

The design of the wall definitely considered sustainability principles. For instance the width and height of the wall was chosen in order to reduce excavation and still continue to satisfy the research purposes of the wall. Excavation can be a hazard and can cause pollution therefore, the design of this wall took serious consideration into that factor as well. The material used in the construction of this wall pertains to the soil bentonite (slurry) and soil from the site. Therefore, mostly local materials are utilized for the research purposes promote economic viability. The resources used in the construction of the wall are important aspects of enriching the economic sustainability since the project will include future job opportunities as well as proper utilization of the resources.

The SB cut off wall serves as a vital component for the research, education and development purposes for the students of engineering at Bucknell University. This wall will serve to study the long term effectiveness of the cut off walls, which is well- connected to the protection and conservation of the environment. This research will allow the study of the flow of contaminants from one side of the wall to the other. Therefore this will help raise awareness about environmental issues. This wall will serve towards learning more important goals of limiting the inward seepage of water to control pollution effects which are an important aspect of

sustainability. The environment can benefit from this aspect hence promoting sustainability. There will not be any degradation done to the environment while conducting the construction process for the wall.

Because the design of this wall is for purposes of research, it is a great opportunity to build social responsibility, awareness and enhance intergenerational equity since this wall will be provided as a tool for any of the Bucknell campus community members to learn and advance in the interested field of geotechnical engineering. This will help enhance the social aspect of sustainability.

Discussion identifying (*ABET C, H*)

- a. the realistic constraints on the project**
- b. how they were addressed in the final design**
- c. the impact of your final design choices in a global, economic, environmental, or social context**

This project had some realistic constraints that fall into varied categories such as economic, environmental, and social. These constraints helped shape the way this project was thought about and ultimately how it was completed. Some of these constraints included, the location of the project, the pending funding for the project, and the construction of the project.

The location of this project produced quite a few constraints. The vertical cutoff wall has been proposed to be built between an active quarry and a protected wetland. This is potentially problematic because if the wall is built too close to the quarry then it could take away from their potential earnings. On the other hand, if the wall is built too close to the protected wetland, then it could disturb the balanced ecosystem that Linn Conservancy has worked so hard to create and maintain. These constraints fall into the categories of environmental, economic, social and potentially political. This was addressed in the final design by having the wall be built in a buffer zone that exists between two properties. This issue will still need to be considered during the construction phase of the project as well though. The cutoff wall's contractor will not be able to store materials on the site of the quarry without Central Builder Supply's permission and similarly will not be able to disrupt Montandon Marsh.

As this project has been proposed for a National Science Foundation (NSF) grant, the funding has not officially been secured yet and poses a potential economic constraint. Despite this, the project team has worked under the assumption that the project will be funded and the design will be used. In this way, this was less of a constraint for the team as it could be for the

principal investigators of the NSF grant proposal. After the project is approved and funded, the principal investigators will be able to further the design and pay for any professionals necessary to do this.

This project has the potential for a large impact to the geotechnical engineering triple bottom line, in terms of economic, environmental and social impacts. Soil-bentonite walls are more sustainable than other cutoff wall methods mostly based on the materials used during their construction and their lack of long-term maintenance or degradation. The two other main types of cutoff walls are sheet-pile walls and secant/tangent pile walls. Sheet-pile walls are made of metal and therefore require an energy intensive manufacturing process. Secant/tangent pile walls are made of concrete which therefore also requires an energy intensive manufacturing process to create the final barrier material of the wall. Also, because both of these types of walls are made of unnatural materials they have the potential to react and damage the ground or become damaged and ineffective over time. Soil-bentonite walls often only require the soil on site being excavated which eliminates the manufacturing process and therefore has economic and environmental benefits. Soil-bentonite walls also generally require less specialized equipment than other cutoff walls and therefore have fewer barriers to entry for contractors which can allow for local contractors to be able to perform this work, thus having a positive social impact.

Reflection on the design process stimulated by the following questions:**a. What would you do differently if you were tasked with completing the project again? And why?**

There were certain segments of the project that could take more time to complete a thorough analysis than what the semester allowed. For instance, we could have done possibly more than two borings in order to be more accurate in our prediction for the soil profiles of the site. In addition to that, these were other tests such as the geophysics test which included the Seismograph test and Ground Penetrating Radar (GPR), that we wanted to conduct. However, due to the limitation of time, we were not able to conduct those tests. This could have given better information regarding the exact alignment of the cutoff. This could have provided us with a more precise location of the bedrock relative to the surface of the soil which would be a large factor when it comes to how the wall should be aligned and what subsurface component will offer the best material to construct the wall. Similarly, some of the laboratory tests such as the permeability, triaxial and consolidation took a little longer than predicted because of less information about how to properly set the lab equipment. This could definitely have been improved for the future.

b. What did you learn that would influence how you will approach project work in the future?

This project was a great experience that influenced us in a positive way. This was a great way to transition into the workforce after school because it provided with vigorous experience on managing and designing various aspects of a project. This is of vital importance since it will provide a great learning experience on how to conduct projects and manage them from the start. The project also helped learn about time management and organization which is a very important aspect for producing good work. Similar to this, this project also helped enabled us to conduct a

lot of field and laboratory work which was an enriching experience. We spent a lot of time learning how to set up equipments and conduct tests for the samples in the lab which is of vital importance. We also gained the ability to analyze our laboratory results which helped us produce good design values for the design of the wall. This project was a good balance of field and lab work overall.

Other than that, there was also a lot of teamwork which is an important aspect of working on projects. There was efficient communication and division of work in the team which helped us meet all our mid semester deadlines on time. The project also involved a lot of self-learning, especially some data calculations and analysis that were needed to be done. For instance, our team did learn a few topics of geotechnical engineering in much depth than we had done previously in our regular courses, such as permeability, trench stability and vertical stress distribution.

The project definitely provided an attitude of willingness to learn and not be hesitant towards approaching a problem. It encouraged team work and approach towards problem solving at a much deeper level. It also influenced time management skills for the better.

c. What was the most difficult portion of the project? And why? How could this have been improved?

The field work that had to be conducted in the cold month of January definitely was difficult. It required concentration and being able to do work effectively at the field. Jim Gutelius definitely was a great resource who helped us at the field site. The laboratory work for the project was tedious and definitely required experience and perseverance. There were several set ups for our permeability, triaxial and consolidation tests, that were required to be reset. Sometimes, we had to set up some of our laboratory set ups more than twice. However, this was

overcome through guidance and advice from our advisor, but it definitely was tedious. Similarly conducting experiments such as the grain size distribution tests for more than 10- 12 samples of soil was tedious but was worthwhile for the completion of the project. After conducting these tests, it was definitely difficult to analyze the results without consulting our adviser. The theoretical values sometimes did not necessarily match the values from the laboratory results and the graphs produced did not show the trend we had expected. So analyzing these data sets were difficult parts of the project. Other than that, there were certain times when the project consisted of new topics that needed more learning and time, which was difficult but an important aspect of the course itself. The design portion of the laboratory work was also difficult. Specifically, finding the 'target grain size' for our soil sample was quite time consuming. Also, the calculations for the design portion that included trench analysis, vertical stress calculations and permeability calculations were difficult. Time managing and being able to meet up with the team mates on a regular basis was also not very easy considering we all had other engineering coursework to complete.

Having mentioned that, these processes are gradual improvements and being able to conduct fieldwork and laboratory work without much difficulty, only comes with experience. So, this was a great learning experience of being in the lab and conducting the tests. There is no faster way to be able to be efficient at this other than more practice and the willingness to learn. However, learning to use the ASTM manuals for the laboratory work was useful and it did make it easier to know the parameters that the lab tests provided. Similarly, the analysis of lab results could have been improved by researching more literature work and books but there was definitely the time limitation. Our adviser guided us on how to perform the analysis on our data which took considerable amount of time but helped us achieve the design for our project.

Discussion of at least one component of the design project that required the design team to self-learn technical subject matter.

Throughout this project we were learning new information regarding slurry walls and the geotechnical field as a whole. We performed lab tests that we were briefly exposed to us at new levels of depth and accuracy, running multiple tests at a time while analyzing the tests that have just finished. However, the design portion of this project required us to learn the most. There were two calculations that we had to learn ourselves before we could complete them. These calculations were the Trench Stability Calculations and the Vertical Stress Distribution Calculations. Both of these calculations required us to research the subject matter and learn the concepts well enough to apply them to our design.

The Trench Stability Calculations are a very specific calculation for slurry wall construction that was not covered in the classes offered at Bucknell. This is because these calculations are again very specific and not very useful for anything other than slurry wall construction. This was very interesting process where we were able to take what we have learned in the past within our classes and then expand on that knowledge with the trench stability calculations. This was a very encouraging situation where we could use our prior knowledge and figure out what was happening in this new situation. In order to acquire this information we were given a chapter out of a book that our advisor Professor Evans is writing at the moment. We primarily used this chapter to learn from and then apply it to our design project where we actually performed the calculation to obtain a design value. The value was then designated as a parameter that will be used during construction.

Similarly, the Vertical Stress Distribution Calculations were something that was not taught specifically to us in our time here at Bucknell. These calculations however, built off of our

prior knowledge more so than the Trench Stability Calculations. With these calculations we had to calculate the stress distribution along the height of the wall. It starts out as a simple effective stress problem but adds a new element of difficulty when the slurry dynamics are added in. It goes from a purely static problem to a combination of static and dynamic. This involved an added shear force along the edges of the soil bentonite backfill which settles after it is dumped into the trench. This mitigates the downward vertical stress on the backfill. Once, we were done performing this series of calculations we came to a maximum vertical stress of 350 psf which is less than 0.25 tsf. This is important because this is the value we used to determine our design permeability and design c_v value.

Both of these calculations were vital with respect to our project. Without teaching ourselves these calculations and learning more about the subjects we wouldn't have had a final design for our project.