

Change in Hydraulic Conductivity of Expansive Soils

by
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A THESIS

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Oregon State University

University Honors College

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the requirements for the
degree of

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(Honors Scholar)

Presented May 9, 2016
Commencement June 2016

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Abstract approved:

John Selker

Swelling soils cause millions of dollars of damage to buildings every year in the Unites States alone. One essential piece to understanding these soils is to understand how water moves through them. Hydraulic conductivity is a measure of how easily water flows through a soil. Currently, the most common method of finding the hydraulic conductivity of a saturated soil is to confine the sample in a rigid container and saturate it for 24 hours, then measure the value and assume that it is constant. This method assumes that the hydraulic conductivity of the soil is not dependent on the swelling of the soil or the length of time that it is saturated. The validity of this assumption was evaluated in this project. The goal of this project is to quantify how the hydraulic conductivity and swelling of the Chilean soil changes over time with continuous saturation, when the soil is allowed to swell freely. A standard soil core was wrapped in latex and submerged it in a sealed jar full of water. Water was then allowed to flow from one end of the soil to the other, and a container was connected to the jar, that allowed water to flow between the two as water was displaced. The hydraulic conductivity of the soil was be calculated at each point in time using mass, pressure, and temperature measurements. The three significant samples used in this experiment each expanded about 10-15% initially then decreased in volume by about 2-3% slowly over time. A total of 90-100 pore volumes were flowed through each sample. Each of the samples initially increased in hydraulic conductivity during the first 24 hours then slowly decreased by about a factor of two in hydraulic conductivity from 1 day to 5-8 days. These data show that the assumption that saturated hydraulic conductivity is constant is violated by real soil.

Key Words: expansive, soil, hydraulic, conductivity

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I understand that my project will become part of the permanent collection of Oregon State University, University Honors College. My signature below authorizes release of my project to any reader upon request.

Johnathon Hesseltine, Author

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Background

Expansive soils can cause large amounts of structural damage. It is estimated that expansive soils cause \$2.3 billion worth of damage per year to buildings, roads, and pipelines in the United States alone. This is more than double the amount of damage caused by floods, hurricanes, tornados, and earthquakes combined. The American Society of Civil Engineering estimates that a quarter of all homes in the United States have damage from expansive soils. Expansive soils are a problem in places all over the world. Figure 1 shows the estimated distribution of expansive soils throughout the world.^{1 2}



Figure 1: Map of expansive soil distribution throughout the world. Areas in black represent locations with high concentrations of expansive soils.³

As indicated in figure 1, there are large amounts of expansive soils through out North America. Expansive soils are also prevalent in Australia, India, and parts fo Africa and the Middle East.

Pore volume is the volume in a porous media which is occupied by fluid. This means that this pore volume is the volume which fluids are able to flow through it. Hydraulic conductivity is a measure of how easily water flows through a porous media.

Equations 1 is used to find the hydraulic conductivity of a sample

$$K = \frac{Q \times L}{A \times \Delta h} \quad (1)$$

¹ King, Hobart. "Expansive Soil and Expansive Clay." Geology.com. 2005. Web. 09 Feb. 2016.

² Case, James C., and Patricia B. Bersie. Wyoming Multi-hazard Mitigation Plan. Cheyenne, WY: Wyoming Office of Homeland Security, 2004. Print.

³ Nelson, John D., Kuo Chieh Chao, Daniel D. Overton, and Erik J. Nelson. Foundation Engineering for Expansive Soils. Hoboken: John Wiley & Sons, 2015. Print.

Expansive soils can change their volume by up to 30 % depending on the level of saturation. This can cause large stresses on structures built within the soil as the level of saturation of the soil changes. These stresses can lead to structural damage to the foundations of buildings. In some places, special building techniques must be used in order to mitigate this risk. For example, some houses are built using a drilled pier and grade beam foundation, where large metal stakes are driven down into the soil and the foundation of the house is all built off those stakes. This is done to isolate the house from the pressures of the expansive soils.⁴

During periods without significant rainfall events soils water evaporates from soils, causing the volumetric water content to decrease. In expansive soils this can cause the soil to shrink, leading to cracking formed within the soil. This can lead to preferential flow patterns in the soil during future rain events.⁵

Clay minerals composed mostly of two main structural units. These include silicon tetrahedrons and aluminum or magnesium octahedrons. Figure 2 shows the structure of silicon tetrahedrons.⁶

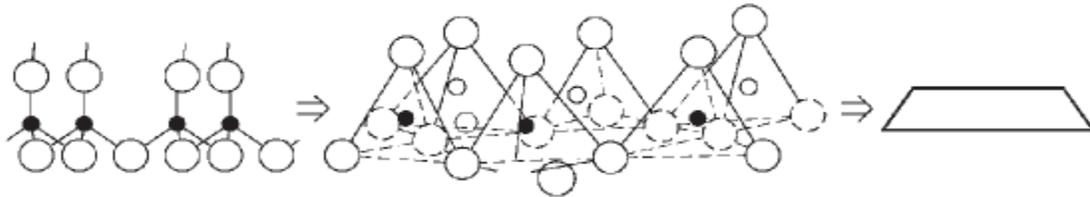


Figure 2: Structure of Silicon Tetrahedrons. Black dots represent silicon atoms and white circles represent oxygen atoms.⁶

Silicon tetrahedrons are made of silicon atoms bonded with four oxygen atoms. These molecules form a tetrahedral configuration. Oxygen atoms have two bonding orbitals, only one of which is fulfilled by the silicon. This causes the oxygen units at the base of the tetrahedral to bond together with silicon atoms from other tetrahedral as shown in the middle part of figure 2. These molecules together form a shape which can be approximated to be a trapezoidal-prism as shown on the right of figure 2. Figure 3 shows the structure of both Aluminum and Magnesium octahedral.⁷

⁴ Nelson, John D., Kuo Chieh Chao, Daniel D. Overton, and Erik J. Nelson. *Foundation Engineering for Expansive Soils*. Hoboken: John Wiley & Sons, 2015. Print.

⁵ Stewart, Ryan D., Majdi R. Abou Najm, David E. Rupp, and John S. Selker. "Measurement Tool for Dynamics of Soil Cracks." *Vadose Zone Journal* 11.2 (2012): 0. Web.

⁶ Nelson, John D., Kuo Chieh Chao, Daniel D. Overton, and Erik J. Nelson. *Foundation Engineering for Expansive Soils*. Hoboken: John Wiley & Sons, 2015. Print.

⁷ Nelson, John D., Kuo Chieh Chao, Daniel D. Overton, and Erik J. Nelson. *Foundation Engineering for Expansive Soils*. Hoboken: John Wiley & Sons, 2015. Print.

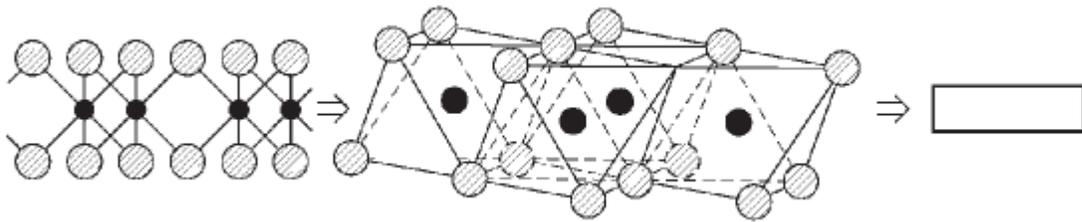


Figure 3: Structure of magnesium or aluminum octahedral. Black dots represent aluminum or magnesium atoms and gray circles represent hydroxyl groups.⁷

Aluminum or magnesium octahedral units are made up of either magnesium or aluminum atoms bonded to hydroxyl groups. These atoms form ionic bonds that are octahedral configurations as shown in the middle section of figure 3. These can be approximated in shape by a simple rectangular prism as shown in the right side of figure 3.⁷

There are three main types of clay minerals. These include kaolinite, illite, and montmorillonite. Figure 4 shows the structure of kaolinite clay minerals.

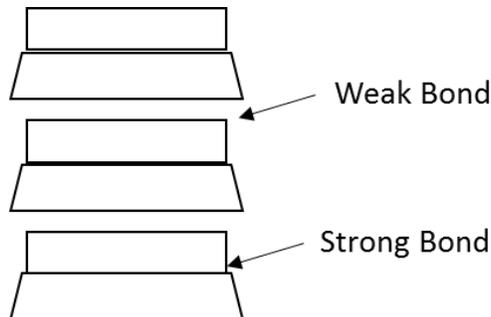


Figure 4: Structure of kaolinite clay minerals. Trapezoids represent silicon tetrahedral units and rectangles represent aluminum or magnesium octahedral units.⁸

As shown in figure 4 kaolinite is made of magnesium or aluminum octahedral units bonded to a single silicon tetrahedral unit. The silicon tetrahedral unit is more electronegative, so there is a slight positive charge on the silicon tetrahedral and a slight negative charge on the aluminum or magnesium octahedral. The Van Der Waals forces cause a weak bond to form between the minerals as shown in figure 4. Figure 5 shows the structure of illite clay minerals.⁸

⁸ Nelson, John D., Kuo Chieh Chao, Daniel D. Overton, and Erik J. Nelson. Foundation Engineering for Expansive Soils. Hoboken: John Wiley & Sons, 2015. Print.

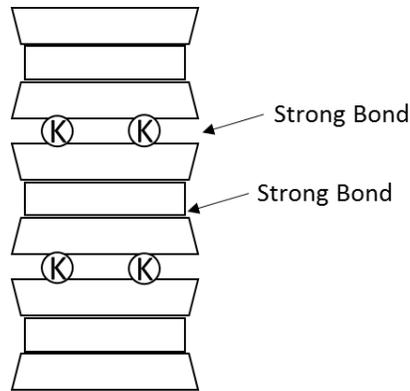


Figure 5: Structure of illite clay minerals. Trapezoids represent silicon tetrahedral units, rectangles represent aluminum or magnesium octahedral units, and circles with “K” in the middle represent potassium ions.⁹

As shown in figure 5 illite is made of magnesium or aluminum octahedral units bonded to two silicon tetrahedral units. Due to the difference in electronegativity, both ends of the have a slight negative charge and the middle has a slight positive charge. Positively charged potassium ions bond between each group to form a strong ionic bond. Figure 6 shows the structure of montmorillonite clay minerals.⁹

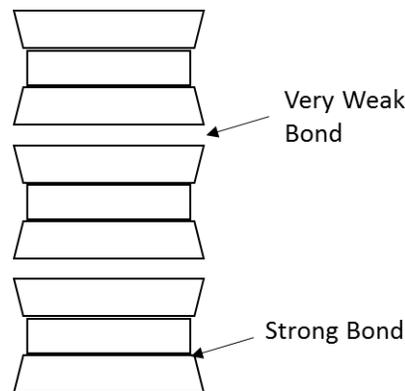


Figure 6: Structure of montmorillonite clay minerals. Trapezoids represent silicon tetrahedral units and rectangles represent aluminum or magnesium octahedral units.⁹

As shown in figure 6 montmorillonite is made of magnesium or aluminum octahedral units bonded to two silicon tetrahedral units. Due to the difference in electronegativity, both ends of the have a slight negative charge and the middle has a slight positive charge, just as it is in illite clay minerals. Unlike illite, there is no positively charged atoms bonding the slight negative charges together. This causes the montmorillonite to form very weak bonds as shown in figure 6.¹⁰

⁹ Nelson, John D., Kuo Chieh Chao, Daniel D. Overton, and Erik J. Nelson. Foundation Engineering for Expansive Soils. Hoboken: John Wiley & Sons, 2015. Print.

¹⁰ Nelson, John D., Kuo Chieh Chao, Daniel D. Overton, and Erik J. Nelson. Foundation Engineering for Expansive Soils. Hoboken: John Wiley & Sons, 2015. Print.

Most expansive clays are made of montmorillonite. The weak bonds between groups and slight polar nature make it easy for water to diffuse between the groups and form bonds. The water pushes the groups apart, causing the soil to expand in size.

Similarly, the soil shrinks back down as water evaporates from the soil and is no longer forcing the molecules apart.¹⁰

Adhesion of water to hydrophilic surfaces can cause capillary forces to occur in small channels. These forces are inversely proportional to the radius of the channel. This affect causes water to preferentially fill smaller pores within a soil during wetting.

Figures 7 to 10 illustrate how the wetting process that occurs in expansive clay soils.

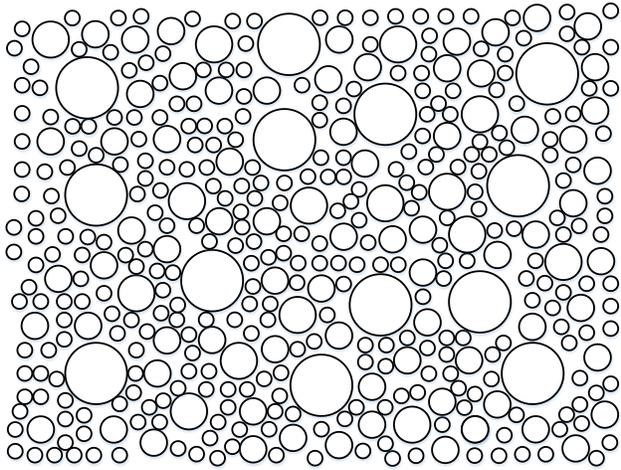


Figure 7: Pores within dry soil

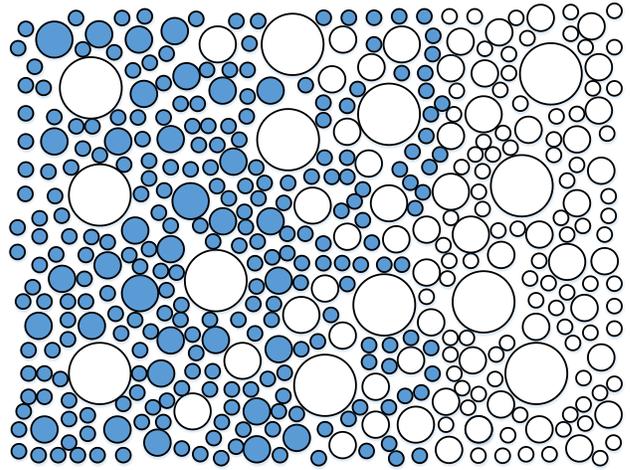


Figure 8: Initial wetting of soil from left to right. Blue indicates pores filled with water and white indicates pores filled with gas.

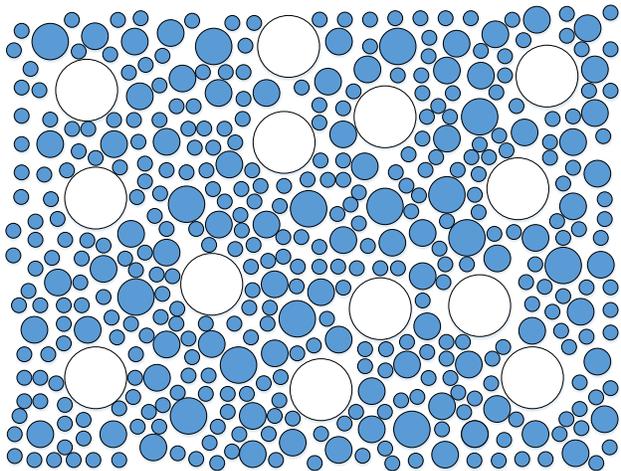


Figure 9: Soil pores after initial wetting. Blue indicates pores filled with water and white indicates pores filled with gas.

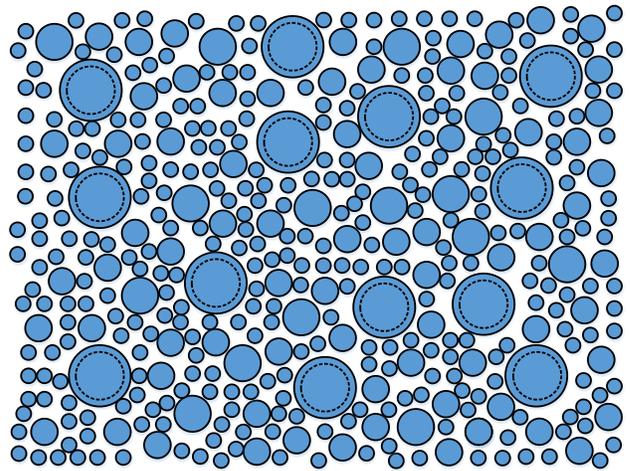


Figure 10: Soil pores after large periods of wetting. Dotted line indicates shrinking of pores over time.

Figure 7 shows the pores in the soil prior to wetting. Figure 8 shows the pores as the soil is initially wetted. As seen in figure 8 the water has progressed farther into the core in the smaller pores than the larger pores due to capillary forces.

Figure 9 shows the soil pores after the sample has been wetted initially. The majority of the pores have been filled. However, some of the larger pores are unable to saturate. The large pores are surrounded by water due to the smaller pores filling faster around them. This causes air bubbles to be trapped in the system. Equation 2 and 3 show Poiseuille's equation and Darcy's Law for capillary flow.

$$v = -\frac{r^2}{8 \times \mu} \times \frac{dP}{dx} \quad (2)$$

$$Q = \frac{\Delta P \times \pi \times r^4}{8 \times \eta \times L} \quad (3)$$

According to Poiseuille's equation the pressure drop due to flow across a capillary is inversely proportional to the diameter to the fourth power at a given flow rate. This means that when saturated it is much easier for water to pass through these larger pores. So, these few large pores have a significant impact on the overall hydraulic conductivity of the soil.

As water continues to flow through the sample vapor trapped in the soil is able to slowly dissolve into the water, leading to the large pores eventually saturating. Expansive soils also swell over long periods of saturation. This causes the pores within the soil to shrink slightly. Figure 10 shows the fully saturated pores shrinking. Field saturated hydraulic conductivity can be greatly influenced by the swelling and shrinking of soils over time. One study found that the field saturated hydraulic conductivity of a swelling soil was 4 to 15 times greater in June and July than during the rest of the year. This is due to larger pores forming in the soil when it is dry that are shrunk back down as the soil is saturated during the months with more precipitation.¹¹

Another study also looked at the seasonal field saturated hydraulic conductivity of two Swedish clay soils. It was found that the soil with a higher capacity for swell/shrink had larger seasonal fluctuations in the field saturated hydraulic conductivity. This is again due to the changes in pore size with extended periods of saturation or drying.¹²

¹¹ Jabro, Jalal D. "Variability Of Field-Saturated Hydraulic Conductivity In A Hagerstown Soil As Affected By Initial Water Content." *Soil Science* 161.11 (1996): 735-39. Web. 29 Apr. 2016.

¹² Messing, I., and N. J. Jarvis. "Seasonal Variation in Field-saturated Hydraulic Conductivity in Two Swelling Clay Soils in Sweden." *Journal of Soil Science* 41.2 (1990): 229-37. Web. 29 Apr. 2016.

Materials and Methods

Soil samples were collected from a site in Chile with expansive soils. The samples were taken using a standard steel soil core sampler at depths between 0 and 81 centimeters. The soil samples were collected in standard brass rings that were 3cm in height and about 5 cm in outer diameter. The samples were shipped back to the Oregon State University. Once there they were oven dried for at least 24 hours. The dried samples were removed from the brass rings. Silicon was used around the edge to attach the soil samples to plastic discs with wire mesh on each side to ensure soil does not get out. The silicon was allowed to dry for at least eight hours. Three layers of latex were then painted onto the soil sample. Each coat was allowed to dry for at least 30 minutes before the next coat was applied. Two latex condoms were then placed over the sample and held in place with black rubber rings. A layer of epoxy was applied between the soil and the latex condom. A vacuum pump was then used to ensure air bubbles were removed.

Each sample was purged with carbon dioxide by flowing at least 10 pore volumes of carbon dioxide through the sample. Carbon dioxide is much more soluble in water much more readily than oxygen or nitrogen. This allows any gas trapped in the sample to dissolve into water much more quickly.

Tubing was attached to both ends of the soil. It was then placed in a glass jar with the soil oriented horizontally. The tubes either end of the soil were run out of the jar through holes bored into rubber stoppers at either side of the jar. The jar was filled completely with tap water that had been de-aired. The inlet side of the soil was connected to a plastic jar filled with a solution of 0.05 molar calcium sulfate. The outlet end of the soil was fed into a plastic container with a funnel over it. The water within the jar was also connected to a standpipe, allowing water to freely flow between the two. The standpipe was covered at the top to avoid evaporation. All four containers were placed onto scales and their masses were recorded overtime. Pressure on the inlet and outlet sides of the soil were measured using a differential pressure transmitter. Figure 11 shows a diagram of the experimental set-up, and figure 12 shows the experimental configuration.

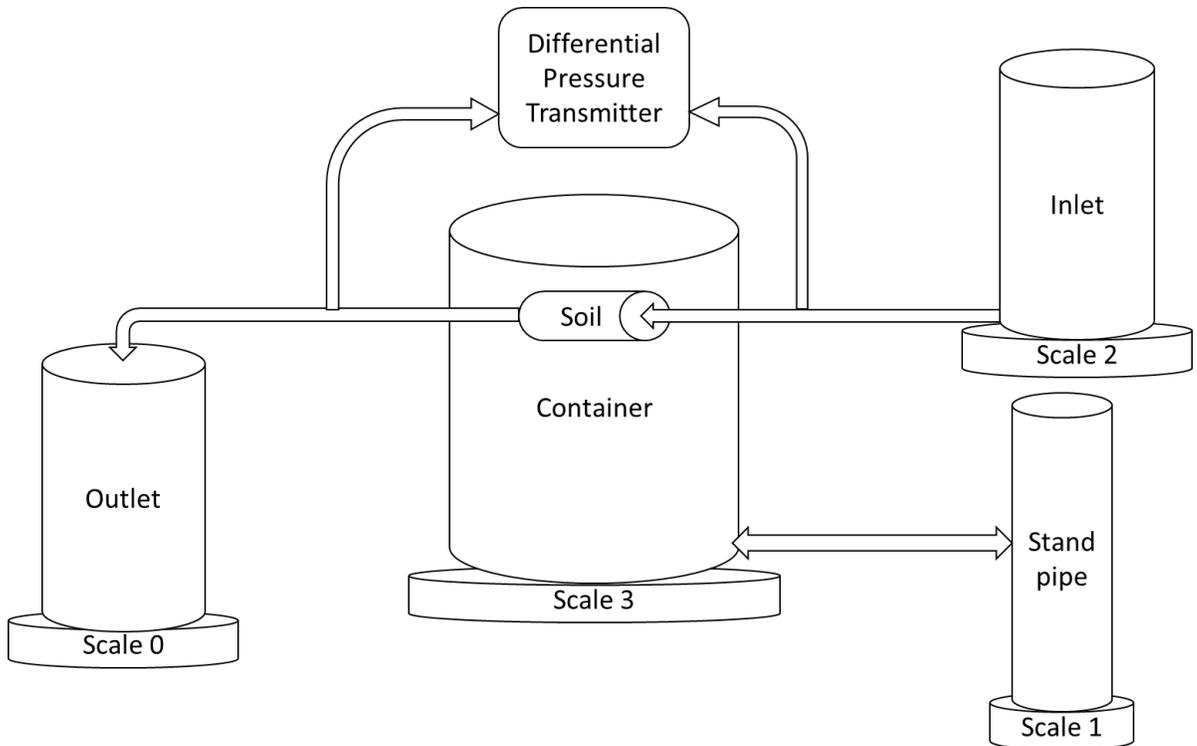


Figure 11: Schematic of experimental set-up.

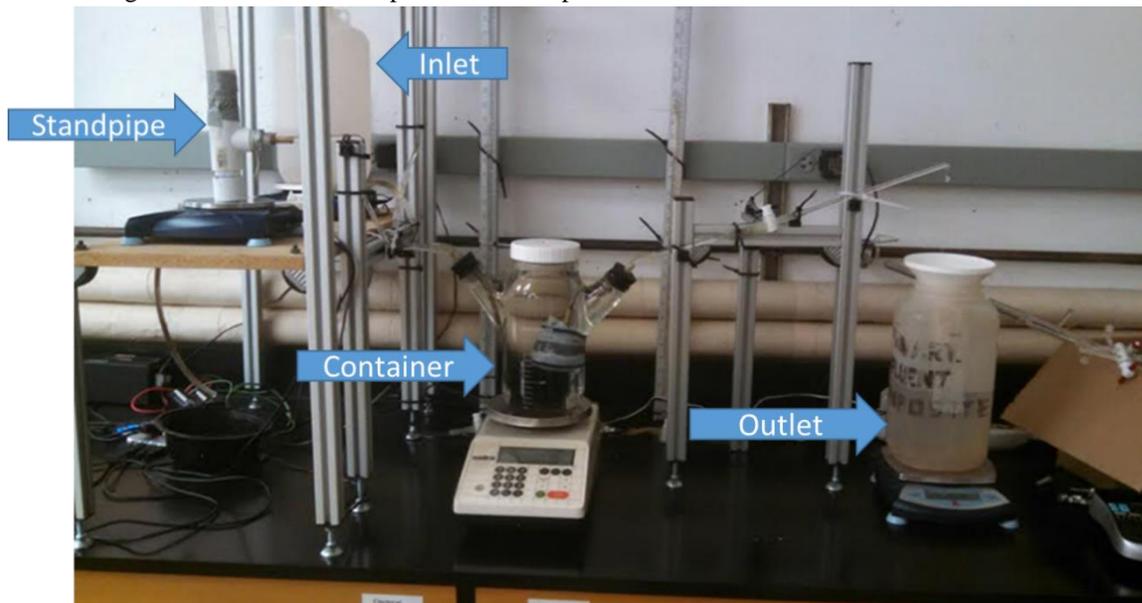


Figure 12: Final experimental set-up.

Samples were placed into the experimental set-up and water was allowed to flow through them. The soil was also oriented vertically within the jar with the inlet side on the bottom of the soil to allow any air bubbles in the soil to escape. When the inlet container got low, the outlet container was poured back into the inlet. After the solution had went through the soil two times it was replaced with a new solution. For samples with relatively low hydraulic conductivity, water was allowed to flow

continuously for at least a week. For samples with relatively high hydraulic conductivity, water was run through the soil for at least 30 minutes. The outlet tube was then shut off allowing the soil to continue saturating without water flowing through it. Water was allowed to flow through the soil again after being saturated for at least 24 hours. A blank sample was made using a brass sampling ring and the same process as the soil samples to be used for calibration. Figure 13 and 14 shows a prepared soil core.

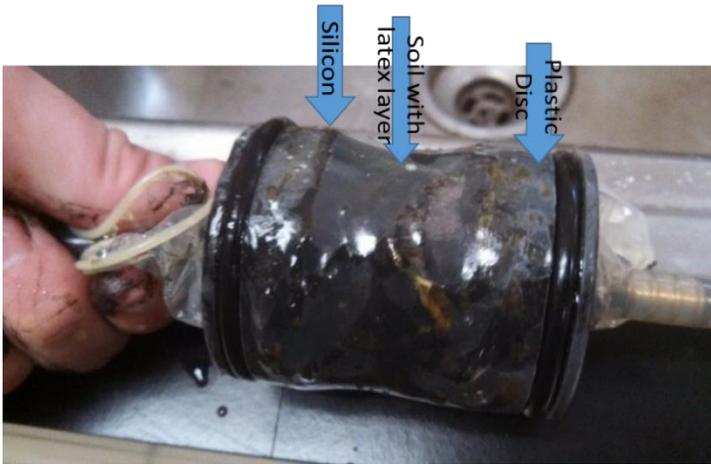


Figure 13: Soil sample configuration



Figure 14: soil sample orientation.

Samples were placed into the experimental set-up and water was allowed to flow through them. The soil was also oriented vertically within the jar with the inlet side on the bottom of the soil to allow any air bubbles in the soil to escape. When the inlet container got low, the outlet container was poured back into the inlet. After the solution had went through the soil two times it was replaced with a new solution. For samples with relatively low hydraulic conductivity, water was allowed to flow continuously for at least a week. For samples with relatively high hydraulic conductivity, water was run through the soil for at least 30 minutes. The outlet tube was then shut off allowing the soil to continue saturating without water flowing through it. Water was allowed to flow through the soil again after being saturated for at least 24 hours. A blank sample was made using a brass sampling ring and the same process as the soil samples to be used for calibration.

The experimental set-up was created using aluminum strut in order to get a stable configuration. Glass tubing in the experimental set-up. The glass tubing was connected to the jars using soft rubber tubing in order to eliminate tension caused by the tubing.

Results and Discussion:

The density of water within the jar changed slightly over time due to changes in water temperature. This caused the mass of water in the jar and the standpipe to be dependent on water temperature as well as the swelling of the soil. A blank sample made from a solid ring was used to find the effect of water temperature measured mass. Figure 15 shows the estimated volume of the blank sample based on standpipe mass measurements before and after the temperature correction was made.

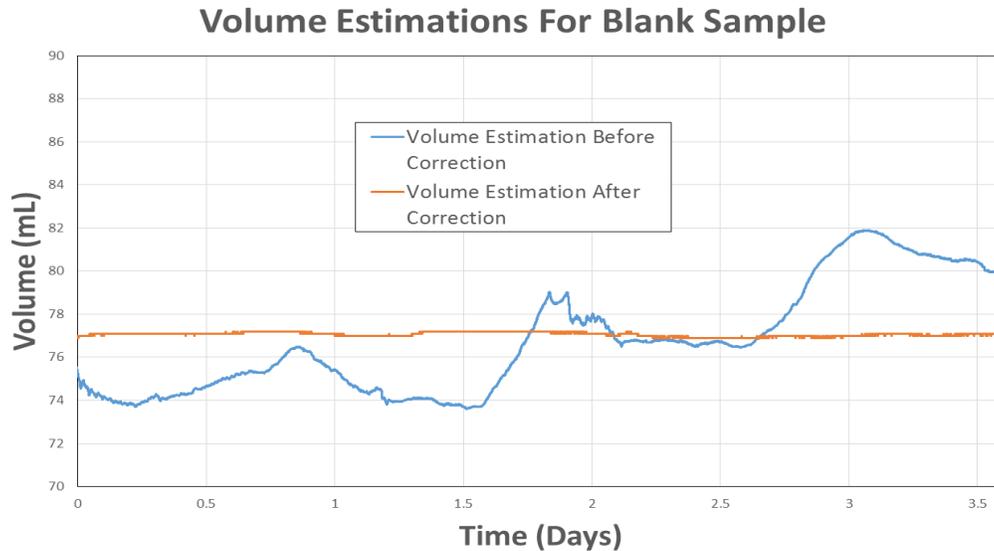


Figure 15: Volume estimations for blank sample based on mass of standpipe before and after temperature correction was made.

It was found that the mass of water within the standpipe could change by several grams. As shown in figure 15 this could have a significant impact on the measured volume of the sample. The same temperature correction was applied to each of the soil sample run in order to eliminate this effect.

Using the methods discussed previously the mass over time of each scale was measured. Figure 16 shows a plot of the data for one of the samples that were run.

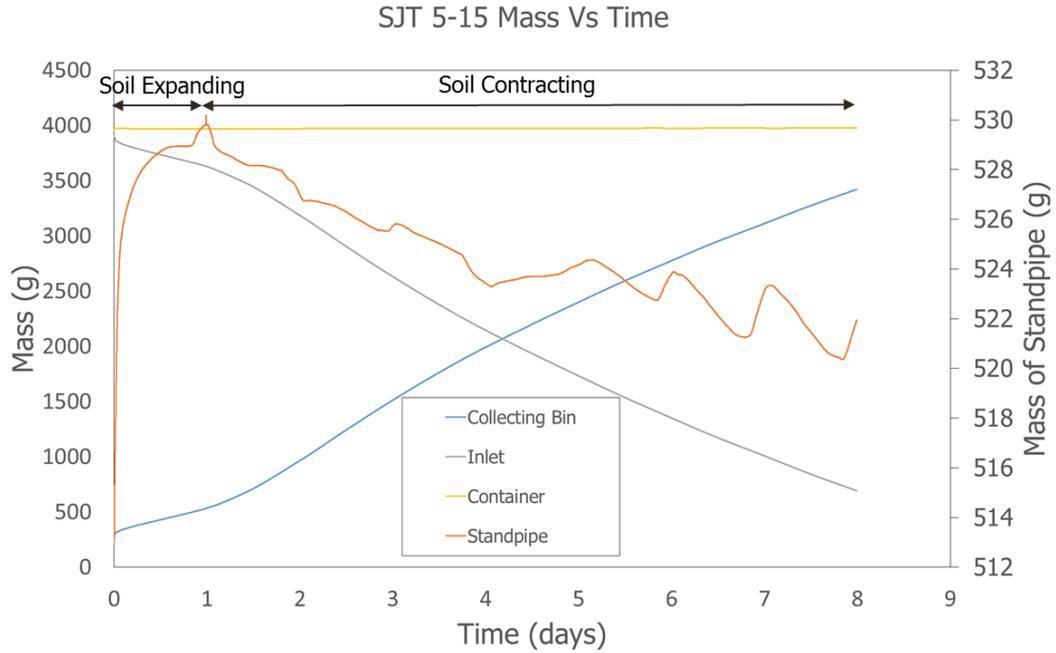


Figure 16: Mass over time of sample SJT 5-15. The hydraulic conductivity was calculated using the change in mass for both the inlet and collecting bin separately. A 20 point moving average was used for the hydraulic conductivity due to low sampling times and low precision in scales. Figure 17 shows the calculated hydraulic conductivity over time.

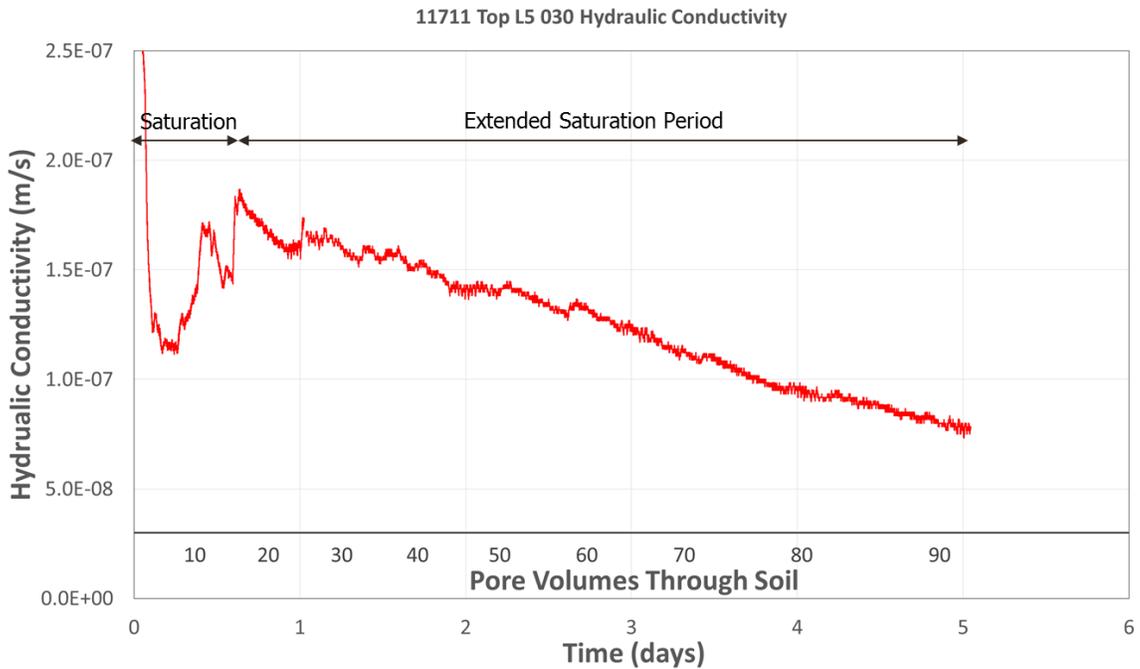


Figure 17: Hydraulic conductivity of soil over time of sample 11711 Top L5 030 calculated using mass of collecting bin.

As shown in figure 17, the hydraulic conductivity of the soil seems to change over time. It is expected to see changes in hydraulic conductivity in the first 24 hours as the soil is fully saturated with water. As discussed in the background some of the larger pores in the sample likely have carbon dioxide trapped in them that is slowly dissolved into the water during the first 24 hours. However, it is commonly assumed that after the first 24 hours of saturation the hydraulic conductivity remains fairly constant. With this sample the hydraulic conductivity decreased overtime after the first 24 hours. The hydraulic conductivity decreases by about a factor of two during the extended saturation period. This is most likely caused by the pores in the soil shrinking as the clay within the soil continues to swell. According to Poiseuille's equation a decrease of about 16% in pore diameter would lead to the hydraulic conductivity being cut in half as seen in this sample. This means the pour volume of the sample is decreasing by about 40%. Figure 18 shows hydraulic conductivity over time of sample SJT 5-15.

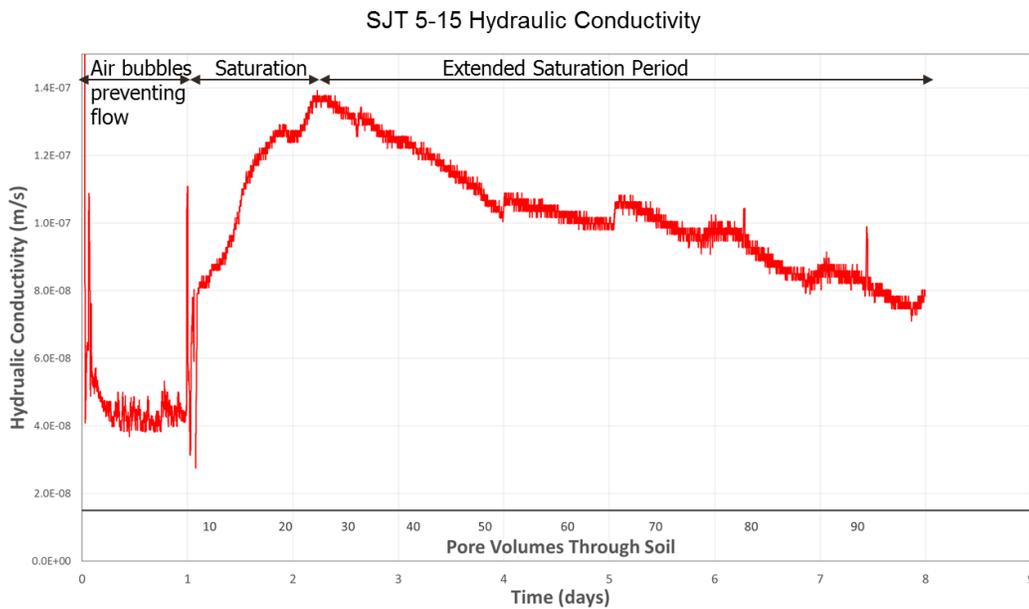


Figure 18: Hydraulic conductivity of soil over time of sample SJT 5-15 calculated using mass of collecting bin.

This sample seems to suddenly increase in hydraulic conductivity after about 24 hours. It was found that there was a small amount of air trapped in the soil. This air was removed using a vacuum pump after at about 24 hours. It is likely that these air bubbles limited flow within the soil and caused the soil to not fully saturate. For this reason, the data recorded in the first 24 hours is likely inaccurate. After the first 24 hours the hydraulic conductivity increases as the sample is likely fully saturating. After about 48 hours the hydraulic conductivity starts to decrease again similar to

sample 11711 Top L5 030. Figure 19 shows hydraulic conductivity over time of sample SJT 4-15 as well as the other two samples discussed earlier.

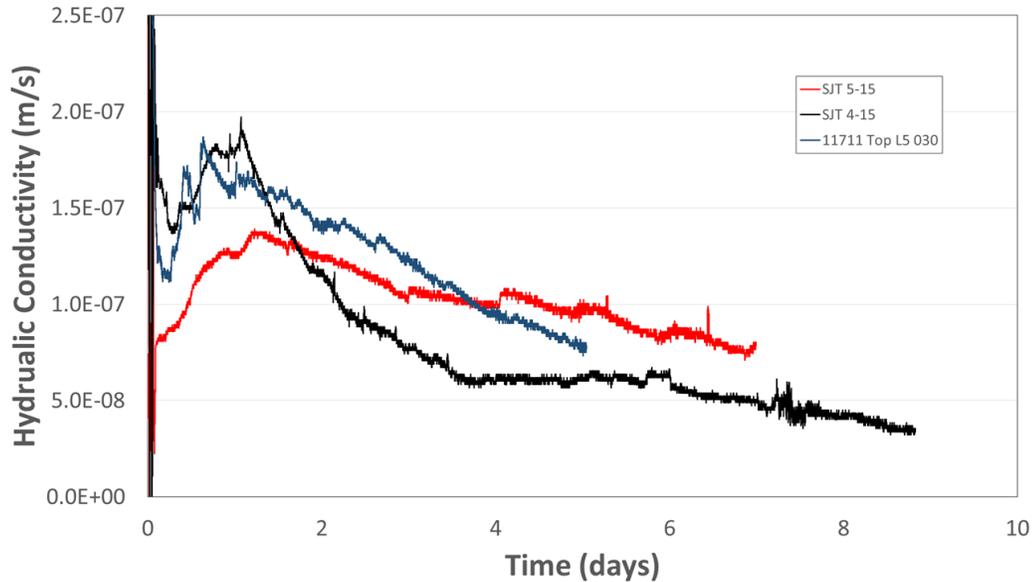


Figure 19: Hydraulic conductivity of soil over time of sample SJT 4-15, 11711 Top L5 030, and SJT 5-15 calculated using mass of collecting bin.

In this sample the hydraulic conductivity once again increases in the first 24 hours as it is saturated. It then decreases slowly over the remainder of the experiment. Each of these three samples expanded by about 10 milliliters in the first 24 hours then slowly decreased in volume for the remainder of the experiment. The plots of volume over time for each of these can be seen in appendix A. Three other samples were tested using the same method, however the hydraulic conductivity of these samples were much lower. The length of these experiments was much shorter, so long term hydraulic conductivity data could not be observed.

All three samples displayed similar behaviors. They all increased in hydraulic conductivity initially as the sample was being fully saturated. They also all decreased in hydraulic conductivity after becoming fully saturated. This shows that the hydraulic conductivity of soils is not constant over time for at least some soils. So, measuring the hydraulic conductivity of soils after 24 hours of saturation may actually overestimate of the long term saturated hydraulic conductivity.

Future Work

With these tests, it is unclear whether this change in hydraulic conductivity is dependent on the time of saturation or the number of pour volumes that flow through the sample. Further testing should be done to measure the hydraulic conductivity of a

sample over long periods of saturation without continuous flow through the sample. This research is enough to question the assumption of constant saturated hydraulic conductivity, but it is not enough to fully characterize how the saturated hydraulic conductivity changes over time for different soil types. Further work should be done using a variety of soil types to further characterize how the saturated hydraulic conductivity changes over time. Further work should also be done to further perfect and standardize this testing method.

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