SOIL PIPING AND INTERNAL EROSION:

LABORATORY EXPERIMENTS ON THE REMOVAL

OF SOIL CLOGS

By

MIKAYLA MARIE WANGER

Bachelor of Science in Biosystems Engineering

Oklahoma State University

Stillwater, Oklahoma

2013

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
May, 2016

SOIL PIPING AND INTERNAL EROSION:

LABORATORY EXPERIMENTS ON THE REMOVAL

OF SOIL CLOGS

Thesis Approved:

Dr. Garey A. Fox

Thesis Adviser

Dr. Daniel Storm

Dr. Tyson Ochsner

ACKNOWLEDGEMENTS

The author acknowledges the financial assistance of the National Science Foundation. I would also like to thank my advisor, Dr. Garey Fox, my committee members, Dr. Storm and Dr. Ochsner, and Dr. Wilson with the USDA ARS National Sedimentation Lab in Oxford, Mississippi. The author also acknowledges Olivia Broussard, Cole Niblett, Hanna Huling, and Abigail Parnell for assistance in data collection and Dr. Ron Miller and Wayne Kiner for assistance in constructing and developing the laboratory setup. This material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. 1144467.

Name: MIKAYLA MARIE WANGER

Date of Degree: MAY, 2016

Title of Study: SOIL PIPING AND INTERNAL EROSION: LABORATORY EXPERIMENTS ON THE REMOVAL OF SOIL CLOGS

Major Field: BIOSYSTEMS AND AGRICULTURAL ENGINEERING

Abstract: Clogging of soil pipes can be detrimental to hillslope stability leading to landscape failures. A soil pipe becomes clogged through internal erosion or pipe collapse; therefore, it is important to obtain more information surrounding these clogging occurrences in order to better predict their effects. When a pipe becomes clogged, a pressure buildup occurs upstream from the clog. This pressure may be enough to remove the clog, or the pressure may continue to build in the soil matrix which could lead to landscape failures. Field observations have indicated occurrences of both, and this study investigated characteristics for which the clog was removed or remained intact. Laboratory experiments were conducted with a 100 cm long clear polyvinyl chloride pipe. A pipe clog was established 90 cm along the pipe length. Triplicate experiments were conducted with two pipe diameters, two soil types (sand and sandy loam), two clog lengths, three pipe roughness, various packing densities, and with both dynamic and constant heads. Digital pressure gauges were installed along the second half of the pipe to monitor pressures both before and after the clog. The upstream pressure and the length of time that the plug withstood the pressure before removal were recorded. Regardless of pressurized time, all clogs were removed as plugs. Adding pipe roughness increased the removal time for the sandy clay loam soil by more than 50%, but had no effect on the sand plugs. The relationship between applied head and pressurized time was a negative exponential relationship. The bulk density had a positive exponential relationship to the pressurized time. In field situations, the hydrology of the water inside of the clog will need to be considered for a model. Data obtained through the experiments outlined above will assist model developers in creating a model for soil piping and internal erosion. This will allow researchers to better understand and predict internal erosion, eventually leading to the ability to prevent major landscape failures.

TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

LIST OF FIGURES

Figure Page

Figure Page

CHAPTER I

INTRODUCTION

Soil Piping and Internal Erosion Background

Soil piping is a major factor in slope stability, and can lead to landscape failures. While there is no widely accepted definition of soil piping, many researchers have given descriptions for the term. The most common definition is that soil pipes are connected chains of subsurface flow pathways that run virtually parallel with the surface flow pathways or hillslope (Uchida et al., 1999; Kosugi et al., 2004; Weiler and McDonnell, 2007; Sharma et al., 2010; Sharma and Konietzky, 2011). Fox and Wilson (2010) define piping as the flow through an open macropore. Macropores can be formed through a variety of biological and physical processes and allow water to rapidly flow through a discrete path beneath the earth's surface. A flowing macropore can be seen in Figure 1.

Figure 1. Water flowing through a macropore at a stream headcut in the Fort Cobb Watershed in Oklahoma.

Jones (2010) defines a soil-pipe as a macropore exhibiting a "water-sculpted form", meaning that internal erosion must be occurring within the macropore. Internal erosion is described by Fox and Wilson (2010) as the corresponding erosion of the soil on the macropore walls during piping. Internal erosion could describe the removal and deposition along pipe walls which could lead to clogging or collapse of the soil pipe. These clogs subsequently cause pore-water pressures to build up in the soil profile surrounding the clog and result in failure of a slope (Uchida et al., 2001). Pipe collapses are often seen on landscapes (Verachtert et al., 2010, 2013), thereby providing evidence after the fact that internal erosion by pipeflow had been occurring below the ground. Wilson et al. (2015a) discusses such internal erosion that is currently taking place on the Goodwin Creek watershed in northern Mississippi. In this watershed, there are layers of loess topsoil above water-restricting fragipan layers making it conducive to pipe formation and internal erosion (Fig. 2 and 3).

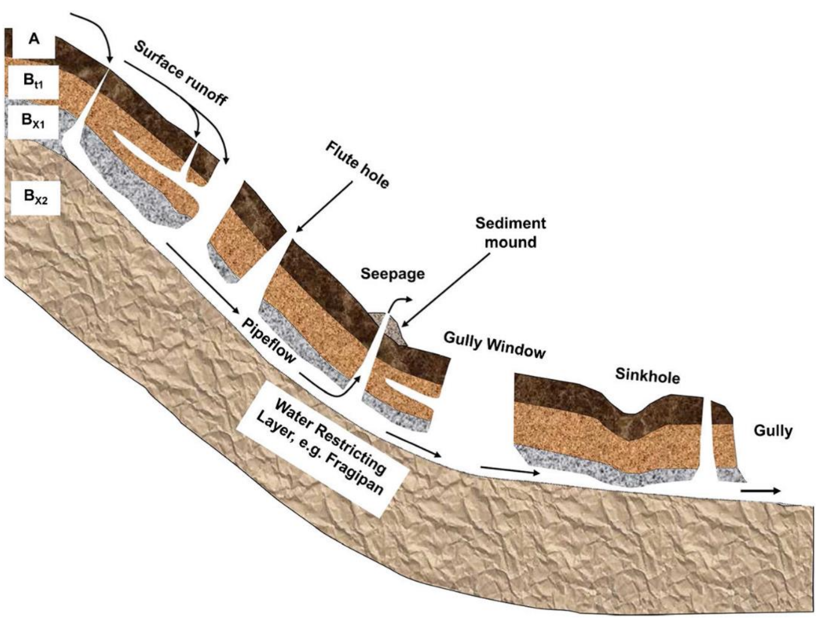

Figure 2. Depiction of a soil profile consisting of two topsoil layers: A horizon and the Bt1 layer and two fragipan layers (Bx1 and Bx2). A soil pipe runs laterally between the fragipan layers and ends in an edge-of-field gully. Many pipe-collapse features can be seen in this slope, such as: flute holes, gully windows, and sinkholes. Each feature allows for interaction between water at the surface and water in the pipes. Source: Wilson et al. (2015a).

Figure 3. Image taken from the Goodwin Creek Watershed of surface features indicating the presence of soil pipes, sink holes, and ephemeral gullies: A flute hole upstream from a gully window (A), multiple flute holes (B), artesian pipeflow (C), and surface flow where water comes up from pipes then reenters pipes through a secondary opening. These features are connected and are indicative of internal erosion and pipe-collapse. Source: Wilson (2015a).

Many of the most dramatic scenarios of soil erosion, e.g. dam and levee failures, landslides and debris flows, streambank failures, and gully erosion, are attributed to soil piping and internal erosion (Pierson, 1983; Foster et al., 2000; Uchida et al., 2001). Previous researchers have shown that fully connected pipe-networks can aid in slope stability through increased drainage (Whipkey, 1965, 1969; Aubertin, 1971; Chamberlain, 1972; Beasley, 1976; De Vries and Chow, 1978). The problem arises when the soil pipe becomes "closed" or becomes clogged through internal erosion or other processes and the water is not able to quickly drain away. The resisting forces of the soil on a hillslope to failure are defined by the modified Mohr-Coulomb equation:

$$s_r = c' + \psi \ \tan\left(\phi^b\right) + \sigma \tan \phi' \quad (1)$$

where s_r is the shear strength of the soil (kPa), c' is the effective cohesion (kPa), σ is the normal stress (kPa), ϕ' is the effective internal angle of friction in degrees, ψ is the matric suction or the difference between the air pressure and pore water pressure (kpa), and ϕ^b is an angle that describes the relationship between shear strength and matric suction (degrees) (Fredlund and Rahardjo, 1993). Fredlund and Rahardjo (1993) assume ϕ^b to be between 10 and 20 degrees and that ϕ^b approaches ϕ' at saturation. When a soil is unsaturated the matric suction of the soil is greater than zero; this means the suction in the soil is adding to the stability of the hillslope. However, as the saturation increases, the matric suction approaches zero which decreases the shear strength of the soil, thus making it more susceptible to failure. When a soil pipe is open the saturation levels are able to decrease quickly through drainage, aiding the stability of the slope, but when the pipe becomes closed the saturation increases and the stability of the slope decreases, which could lead to landscape failures (Fig. 4).

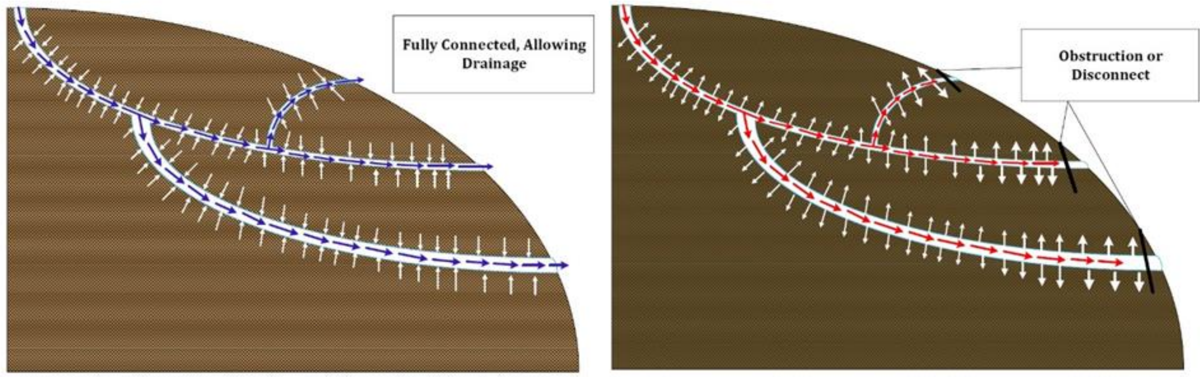

Figure 4. Hillslope with a fully connected soil pipe flow network (left) allowing water to leave the slope more quickly by traveling through soil pipes, decreasing the saturation of the soil and allowing for increased slope stability; and a hillslope (right) in which the soil pipes have been somehow disrupted and no longer allow flow out of the slope, creating an increase in pore-water pressures and saturation which decreases the slope stability leaving it susceptible to landscape failures.

Many studies have been conducted more recently on soil pipe clogging and its implications on landscape failure. Pierson (1983) found that a blocked pipe passageway can lead to pore-water pressures within the pipe that are much greater than those associated with saturated soils, and these pressures could trigger landslides. Sun et al. (2012) performed laboratory experiments and had similar findings. They found that once a pipe-flow network was disturbed or damaged the water levels in the upper levels of the slope increased, decreasing slope stability. In laboratory experiments using a constant flow into constructed soil pipes, Wilson (2009) found that the outflow would occasionally stop followed by periods where a large amount of sediment would be dispelled from the pipe and flow would continue. This shows that internal erosion is occurring and causing the soil pipe to become clogged. When the clogs occurred, there was a measurable increase in the pore-water pressure in the soil matrix surrounding the clog. Wilson noted that the increase in pressure in the matrix was likely not representative of the pressures inside of the soil pipes due to hydraulic non-equilibrium. In situ soil pipe experiments conducted by Midgley et al. (2013) showed that there was a pressure increase in the soil matrix adjacent to a clogged soil pipe and that the pressure increase was the highest within the soil pipe clog. These experiments also showed that low density clogs were removed while higher density clogs were resilient against removal. Both the Wilson and Midgley experiments lack the ability to note the pore-water pressures inside of the soil pipe itself, which could be an important indicator in landscape failures as these pressures could lead to saturation of the soils surrounding the soil pipes and reducing the resisting forces.

Modeling Background

Currently, water flow in soil pipes has been modeled using two methods: treating the pipe as a part of the matrix with a high hydraulic conductivity or as an underground stream system. The most common method of modeling soil pipes is treating the soil pipe as a highly conductive flow path by utilizing Richards' equation to model flow (Wilson and Fox 2013). These models assume static pipe diameters with no expansion due to internal erosion or assume symmetrical expansion of the macropore. As the pipe diameter expands, the flow area increases which could potentially increase the flow rate through the pipe if a large enough pressure head is available. These models also cannot handle situations where the sediment transport capacity overcomes the transport ability or a collapse clogs the open soil pipe resulting in the buildup of pore-water pressure.

Wilson et al. (2015b) performed tracer injection tests at the Goodwin Creek Watershed; they found that flow lengths, flow velocities, and pipe sinuosity fit closely to that of streams. In this study, Wilson et al. also discovered that the velocities within the soil pipe created forces that were larger than the critical shear stress of the soil, indicating that internal erosion was in fact occurring. Zhou et al. (2016) utilized the tracer data from Goodwin Creek and the transient storage model OTIS-P to assess the capabilities of modeling soil pipes as stream systems. The model gave breakthrough curves similar to those acquired through tracer tests, but there was considerable variability in transport parameters that was likely attributed to irregularities throughout the pipe network, interaction with smaller flow systems, and potential retention within collapsed portions of the pipe. The limitation in this model was that it only characterized the pipe characteristics for a single instance in time. If further internal erosion occurs, the flow and transport characteristics may change.

Study Objectives

Considering the large number of landscape processes that may be influenced by soil piping and internal erosion considerable research advances are still needed. Through innovative laboratory experiments the mechanisms associated with soil pipe clogging and the corresponding pressure increase within the soil pipe can be better defined and quantified. In order to understand and eventually develop improved models for internal erosion and soil piping, this research investigated the pressure buildups that occur due to pipe clogging, along with conditions for clog removal, in a simplified soil pipe system. Information is needed about pressures required to remove a pipe clog in order to understand when and if the pipe continues to remain clogged or if the pipe reopens to drain the hillslope. This objective of this research is to answer questions regarding how characteristics of a plug affect the instantaneous pressure buildups behind soil clogs, and if the pressure buildup is sufficient for plug removal to reopen the pipe or if the clog will withstand the pressures and destabilize the hillslope. In order to achieve this, plugs were created with different soil textures, lengths, packing moisture contents, bulk densities, plug diameters, and pipe roughness, and pressures inside of the soil pipe were be monitored until the time of plug removal.

CHAPTER II

METHODS AND MATERIALS

Soil Characterization Tests

Two soil types were used for the piping experiments: coarse sand and sandy loam soil excavated from Cow Creek in Stillwater, Oklahoma. Soil characterization tests were performed to better understand the dynamics of the soil used in piping experiments. Some tests were run based on the soil itself, and others based upon packing characteristics. The soil characteristics along with packing characteristics such as bulk density, moisture content, and contact area of the clog on the pipe, were evaluated to determine relationships between soil characteristics and clog removal.

Particle Size Distribution

Particle size distribution was used as an indicator for both the plug material and also the pipe roughness as the soils were used to roughen the pipe walls. Particle size distribution was determined for each soil using hydrometer and sieve analyses following ASTM Standard D422. The soils were used both for packing the plug and for adhering to the pipe wall with a waterproof resin to change the roughness.

Saturated Hydraulic Conductivity

Laboratory observations of pipe clogging experiments showed that many of the plugs approached saturation before their removal. These observations led us to believe that the saturated hydraulic conductivity could play a role in plug removal. A UMS KSAT Machine (Fig. 5) was used to determine the saturated hydraulic conductivities for the soils when packed to different bulk densities. Samples were packed to the same bulk densities as were used in the piping experiments. Replicate tests were performed on packing bulk densities of 1.3, 1.4, 1.5, and 1.6 g cm^{-3}. Each sample was saturated from the bottom using the protocol outlined by the machine's manufacturer, and then the machine performed falling head tests on the samples with water as the fluid. A table was then created to observe changes in saturated hydraulic conductivity due to soil type and bulk density.

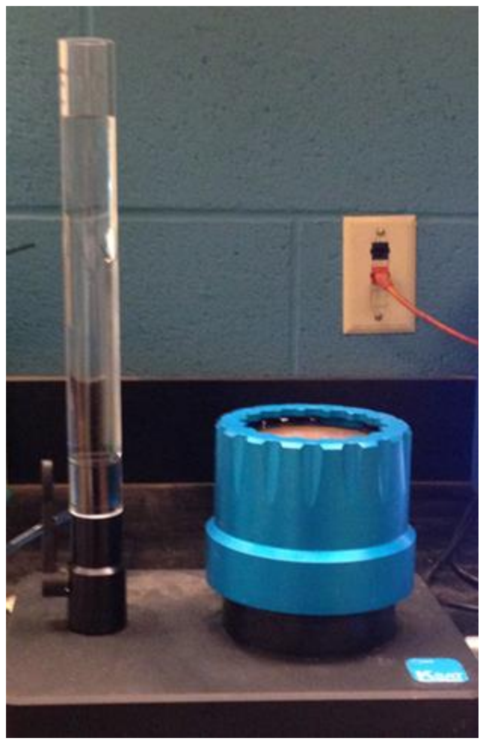

Figure 5. Saturated hydraulic conductivity machine running a falling head test on one of the soil samples.

Atterburg Limit Test

Soil plasticity is a major indicator of landscape failure susceptibility and also could play a role in plug removal characteristics. A highly plastic soil with a high clay content is likely to change volume when water is added or removed. Adding water to a highly plastic soil, usually a fine-grained soil, can cause it to lose approximately 99% of their inherent shear resistance to sliding (Carter and Bentley, 1991). Both of the soils used in this study were granular and Atterburg Limit Tests indicated that they were non-plastic, but in a more fine grained soil, the plasticity and corresponding moisture content could be important when considering critical pressures for plug removal.

Laboratory Piping Experiments

Baseline laboratory experiments were conducted using a 100 cm long artificial soil pipe made of clear polyvinyl chloride pipe equipped with five pressure transducers across the back half of the pipe. A polyvinyl choride pipe is used to represent the soil pipe in order to measure the pressures inside of the pipe. In previous experiments where actual soil pipes were used, a pressure increase was measured within the soil matrix, but not within the soil pipe itself. A plug with certain characteristics was then packed 10 cm from the pipe outlet, between the fourth and fifth pressure transducers. A peristaltic pump was utilized to increase the head at a constant rate between 0.75 to 1.5 L min^{-1} for dynamic head experiments, and a constant head tank was utilized to maintain a constant head ranging from 10 cm H_2O to 100 cm H_2O for those experiments. A scale placed at the end of the setup recorded the outflow for each experiment (Fig. 6). Experiments were conducted with sand and sandy loam soils, 3 cm and 6 cm plug lengths, 20 mm and 30 mm pipe diameters, three pipe roughness values, 12%, 15% and 20% moisture contents at packing, and bulk densities ranging from 1.3 g cm^{-3} to 1.6 g cm^{-3}. Triplicate experiments were run for each experimental variable; a list of the 394 experiments conducted can be found in Appendix 1. Pressure transducers (Omegadyne PX409-USBH) were connected to a computer and recorded the pressure within the soil pipe every 0.1 s. The maximum pressure reading for the transducers was 176 cm H_2O.

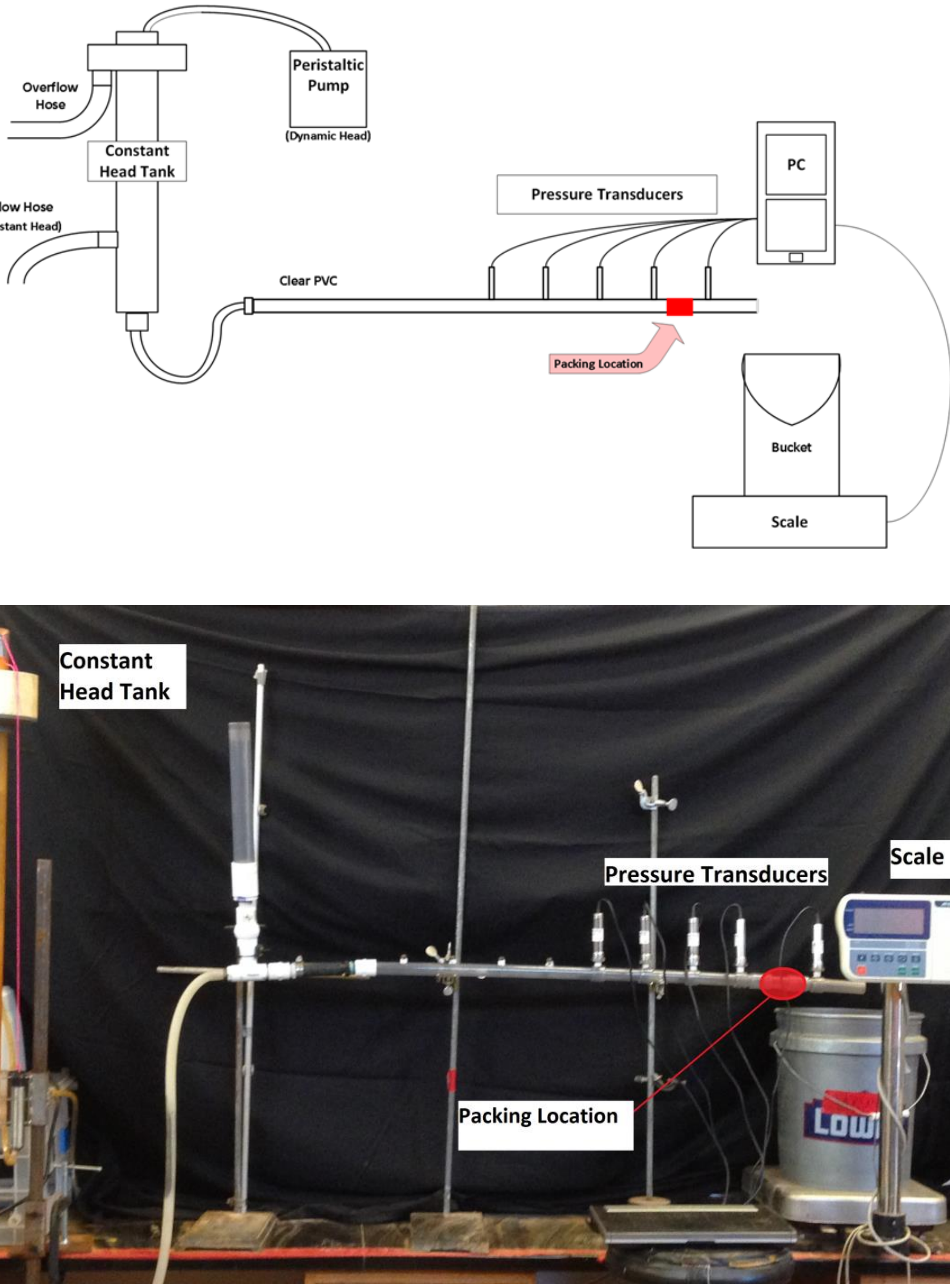

Figure 6. Diagram of laboratory setup including the constant head tank, pressure transducers, and scale to measure outflow (top), and an image of the actual laboratory setup (bottom). A peristaltic pump was used to pump water at a constant rate into the constant head tank, where the head increased at a constant rate for dynamic head experiments. The constant head tank was raised or lowered to certain applied heads and remained completely full for constant head experiments.

Dynamic Head Experiments

Dynamic head experiments were representative of what would happen on a hillslope during a rainfall event. The head was increased until the point when the plug was removed, or the pressure was enough to cause landscape failure. Dynamic head experiments were conducted to determine the critical pressures at which clogs were removed. Experiments were conducted for a range of soil characteristics which served as experimental variables: two pipe diameters, two soil types, two plug lengths, four bulk densities, and three moisture contents at packing. In these experiments water was pumped into a tank at a constant rate ranging from 0.75 and 1.5 L min^{-1}. Within this tank, the water rose at a constant rate increasing the head that was applied to the plug. This continued until the critical pressure was reached and the plug was removed or until the tank reached the maximum possible head (95 cm H_2O), at which point the head remained constant until the plug was removed. The tank was set to a maximum of 91 cm of head to ensure that sensor noise would not exceed 176 cm H_2O, at which point the sensor stops recording data. All plugs were removed intact so pipe roughness was added as a variable. Pipe roughness was changed by adhering sand or sandy loam to the inside pipe walls using a waterproof resin (Fig. 7).

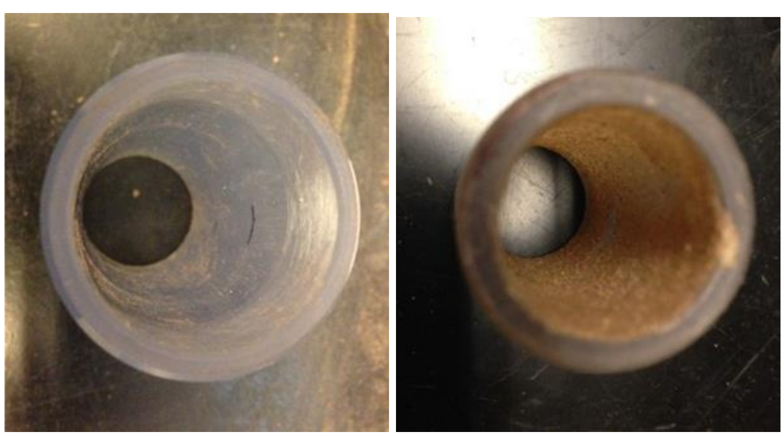

Figure 7. Smooth walled polyvinyl chloride pipe (left) and sand adhered to the inside pipe wall to increase the roughness of the pipe (right).

Constant Head Experiments

Constant head experiments were representative of a hillslope next to a reservoir, such as a dam. Constant head experiments were conducted to determine the critical time that a soil plug could withstand an applied head. In the dynamic head experiments, when the head reached the maximum allowable pressure, the removal became time dependent. This led us to consider the critical time for different constant head values. Constant head experiments were conducted for two pipe diameters (20 and 30 mm), two soil types (sand and sandy loam), two plug lengths (3 and 6 cm), and four bulk densities (1.3, 1.4, 1.5, and 1.6 g cm^{-3}). Experiments were also conducted for several different constant head values: 10, 25, 50, 75, and 100 cm H_2O. Again, all plugs were removed intact and pipe roughness was added as a variable.

Impulse Calculations

In order to compare dynamic and constant head experiments it was necessary to develop a scale with which the two were compatible. Integrating under the curve given by the pressure transducer (applied pressure with respect to time) then multiplying by the surface area of the plug determined impulse (*Imp*) based on both the pressure applied and the length of time:

$$Imp = \int_{t_1}^{t_2} P(t)dt \quad (2)$$

where P was the function of pressure with respect to time, t_1 was the initial time at which the pressure begins, and t_2 was the time of plug removal. Impulse is similar to the hydrograph area used by Detty and McGuire (2010), obtained by integrating an increase in the groundwater table, or change in water height within a well, over the duration of a storm event. In the dynamic head experiments, the pressure changed over time giving two possible shapes for impulse area depending on whether or not the maximum applied pressure was reached before the plug was removed. When the maximum pressure was not reached, the pressure increased at a constant rate, then once the plug was removed, dropped off sharply (Fig. 8a). When the maximum pressure was reached before removal, the pressure leveled off at the maximum pressure until the plug was removed and the pressure dropped off (Fig. 8b).

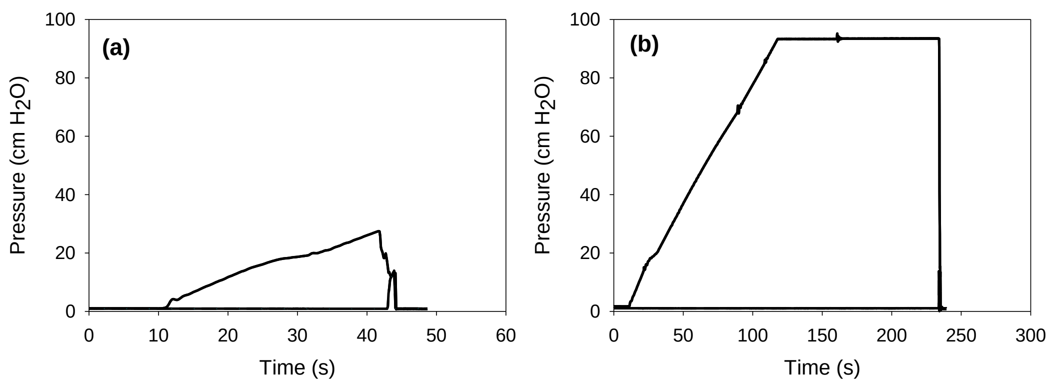

Figure 8. Sample output from pressure transducers for dynamic head experiments. Two basic shapes are formed: (a) Sand, 1.6 g cm^{-3} bulk density, 12% moisture content, 6 cm length, and 1 L m^{-1}. The plug reached a critical pressure of about 30 cm H_2O and was removed; and (b) sandy loam soil, 1.6 g cm^{-3} bulk density, 12% moisture content, 6 cm length, 1 L m^{-1}. The plug withstood a constant maximum possible applied pressure of 95 cm H_2O, and then was removed after a period of time at that head.

In the constant head experiments, the applied pressure was constant and therefore no longer a function of time. These experiments also gave two distinguishable curves. Some plugs did not withstand the initial force that was applied to them and were removed almost instantaneously (Fig. 9a). For these plugs, the critical pressure would be somewhat lower than that which was applied. Plugs that did withstand the applied pressure would remain at that pressure for a certain amount of time and then the pressure would drop off upon plug removal (Fig. 9b).

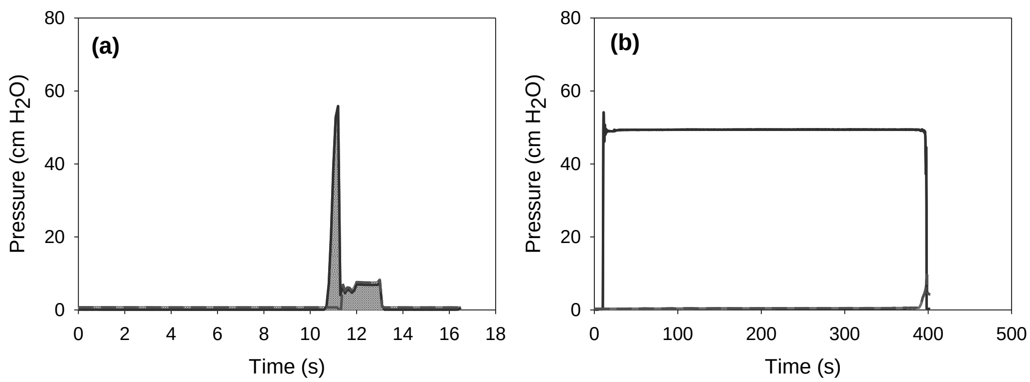

Figure 9. Example outputs from pressure transducers for constant head experiments. Two basic shapes were formed: a) Sand, 1.6 g cm^{-3} bulk density, 12% moisture content, and 3 cm length, at 100 cm applied head and b) Sandy loam soil, 1.6 g cm^{-3} bulk density, 12% moisture content, and 6 cm length, at 50 cm applied head. The sand plug never reached the applied head and was removed nearly instantaneously upon the pressure being applied. The sandy loam soil withstood the applied pressure for more than 500 seconds before it was removed.

Statistical Tests

First, comparisons were made between constant and dynamic head experiments to determine if data could be combined. These data were plotted in box plots and normal data were compared using a two-tailed t-test and non-normal data were compared using the Mann-Whitney Rank Sum tests. These analyses determined whether the differences between the mean values of the constant and dynamic head experiments were greater than would be expected due to random chance. If the means were not significantly different, these data could be combined for further analysis.

Once these data were combined, one-way ANOVA was used to determine whether experimental variables were significant factors in plug removal. These data were plotted in a box plot and the statistical test was run allowing letters to be added to the plots showing where differences were significant with non-significant differences sharing the same letter, and significant differences having different letters. Where there was a significant difference, the experimental variable was important in the plug removal process.

Calculation of Wetting Front Migration

Wetting front migration within plugs was calculated for the constant head experiments to compare the plug removal times to the time for the wetting front location to propagate through the plug. Due to the assumption of a constant head, this analysis was not conducted on the dynamic head experiments. Using a simplified version of Darcy's unsaturated flow equation for a horizontal region for a wetted thickness, L_f, the flux through the plug, q was given as:

$$q = -K_{SAT} \frac{h_0 - h_f}{L_f} \tag{3}$$

where h_0 is the applied constant head, h_f is the matrix suction head at the wetting front, and K_{SAT} is the saturated hydraulic conductivity of the soil. The h_f was estimated from Rawls et al. (1983) where the author compares the Green-Ampt parameters of nearly 5,000 soil horizons. Utilizing conservation of mass the cumulative infiltrated amount, Q, was the same as the wetting front distance times the change in soil water content, $\Delta\theta$:

$$Q = L_f \Delta\theta \rightarrow q = \Delta\theta \frac{dL_f}{dt} \tag{4}$$

where t is time. Combining the two above equations equations and integrating:

$$\int_0^{L_f} L dL = K_{SAT} \frac{\Delta h}{\Delta\theta} \int_0^t dt \rightarrow \frac{{L_f}^2}{2} = K_{SAT} \frac{\Delta h}{\Delta\theta} t \tag{5}$$

which can be rearranged to find the time to achieve a certain wetting front distance in the clog. Observed times to plug removal were then compared to predicted times for the wetting front to propagate to a certain distance through the clog.

CHAPTER III

RESULTS AND DISCUSSION

Soil Characterization Tests

Particle Size Distribution

Hydrometer tests were used to determine the particle size distribution of the soils used in the dynamic and constant head experiments. The sand soil was 98% sand with d_{16}=0.11 mm, d_{50}=0.20 mm, and d_{84}=0.35 mm. The sandy loam soil possessed 65% sand, 30% silt, and 5% clay with d_{16}=0.04 mm, d_{50}=0.06 mm, and d_{84}=0.50 mm. These results were important to characterize soil plugs and pipe roughness. The sand was more coarse and less cohesive than the sandy loam soil (Fig. 10). The soils used in the experiments were less cohesive than would likely be seen in real world scenarios. Sandy soils are not conducive to pipe formation and the majority of soil pipes will occur in more cohesive soils. Sand particles require higher forces to move, therefore most plugs formed through internal erosion will likely be more cohesive than sand plugs. However, these soils provided a base line for understanding critical pressures and times for clog removal.

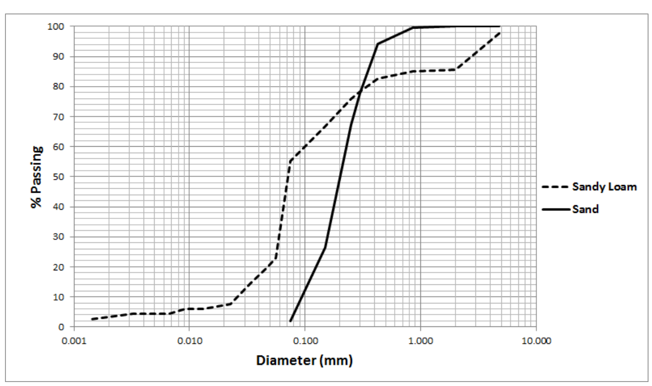

Figure 10. Particle size distribution for sand and sandy loam soils used in the laboratory experiments.

Saturated Hydraulic Conductivity

As expected, the soils' conductivity increased as the packing bulk density decreased (Table 1). The water moved faster through the lower bulk density samples as there was more available pore space. The lower bulk density soil plugs saturated at a faster rate, which could be a mechanism for their faster removal or removal at lower pressures. Matthews et al. (2010) reported similar findings on how compaction effects saturated hydraulic conductivity. For the soils in their experiments, they found that decreasing the porosity through compaction significantly reduced the saturated hydraulic conductivity (Fig. 11).

Table 1. Saturated hydraulic conductivity for packed soil clogs. Results are the averages of three tests for each experimental variable. All samples were packed at 12% moisture content.

Soil	Bulk Density ($g\ cm^{-3}$)	Saturated Hydraulic Conductivity ($cm\ d^{-1}$)
Sandy Loam	1.6	6.00
	1.5	8.00
	1.4	36.5
	1.3	52.0
Sand	1.6	182
	1.5	425
	1.4	488
	1.3	735

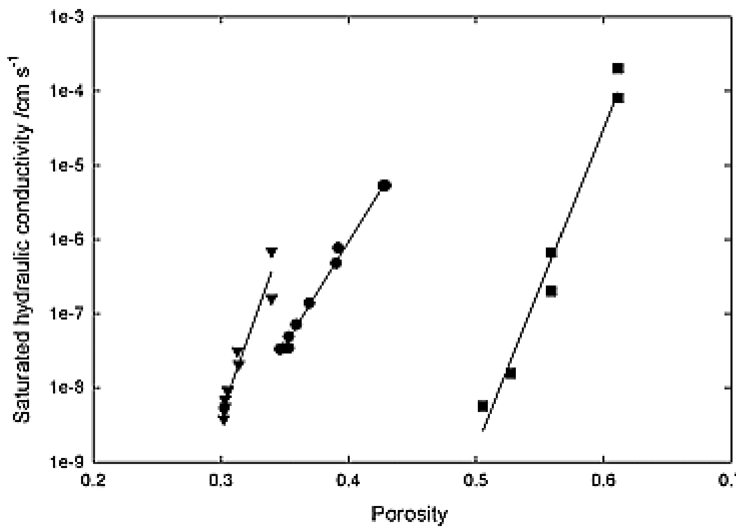

Figure 11. Effects of compaction on saturated hydraulic conductivity. Source: Matthews et al. (2010).

Atterburg Limit Test

The Atterburg Limit Test showed that the soils used in this experiment were non-plastic. This was expected considering the particle size distribution for both soils indicated coarse grained soils. If the soils were plastic, they would have been expected to experience drastic changes in volume with changing moisture contents. These processes would need to be considered within future internal erosion and pipe clogging models.

Laboratory Piping Experiments

Dynamic Head Experiments

All soil clogs were removed as intact plugs, regardless of soil type or pipe roughness. Most plugs approached saturation before removal, which was observed by watching the wetting front move across the plug through the clear pipe. Some were removed easily, such as the sand plug shown in Figure 12a, which was removed in less than a minute at approximately 28 cm H_2O. Others exceeded the maximum allowable pressure of 95 cm H_2O and then removal became time dependent (Fig. 12b). Maximum pressure was held at 95 cm H_2O to ensure sensor noise never exceeded the sensor maximum of 175 cm H_2O, upon which the sensor stopped recording data. The sensor located downstream of the clog increased right before plug removal as the plug moved past the sensor, but the pressure never reached the applied head.

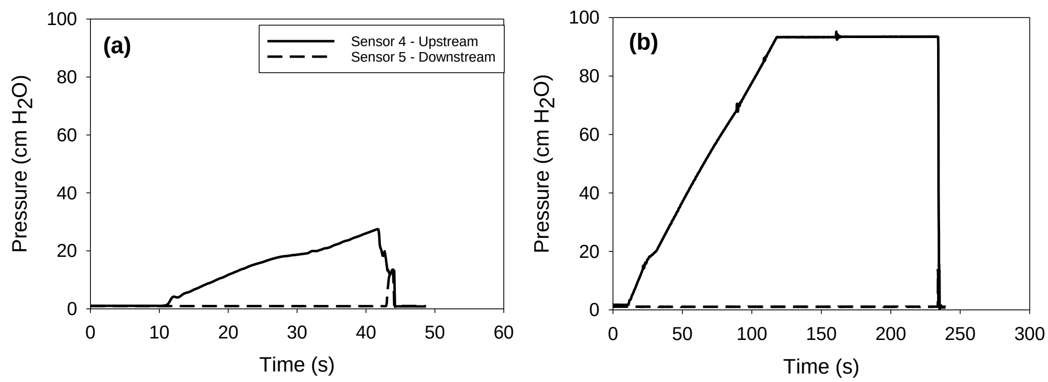

Figure 12. Sample output from pressure transducers: (a) Sand, 1.6 g cm^{-3} bulk density, 12% moisture content, 6 cm length, and 1 L m^{-1}. The plug reached a critical pressure of about 30 cm H_2O and was removed; and (b) sandy loam soil, 1.6 g cm^{-3} bulk density, 12% moisture content, 6 cm length, 1 L m^{-1}. The plug withstood the maximum possible applied pressure of 95 cm H_2O, and then was removed after a certain amount of time at that head.

Increasing the moisture content at packing influenced the removal of the soil clogs for both soil types when graphed directly from the data (Fig. 13). The sandy loam plugs were removed at lower pressures as moisture content increased. The most likely reason for this result was that the increase in packing moisture content brought the sandy loam soil closer to saturation, thereby reducing the time to lubricate the wall enough to remove. As mentioned previously in most cases, the wetting front could be observed moving through the plug, and the plug was removed at some point along that wetting front. The sand plugs were removed at a higher pressure for those packed at 15% moisture content than 12% moisture content, and the plugs were removed at a lower pressure for those packed at 20% moisture content. This could have been due to a slight added cohesion from adding moisture to the 15% plug and the plug already being fairly lubricated along the pipe wall for the 20% plug. The 6 cm sandy loam plug packed to 12%

moisture content exceeded the maximum possible pressure and then removal became time dependent. All experiments required more than 95 cm H_2O for removal which is why the variation between those experiments was small.

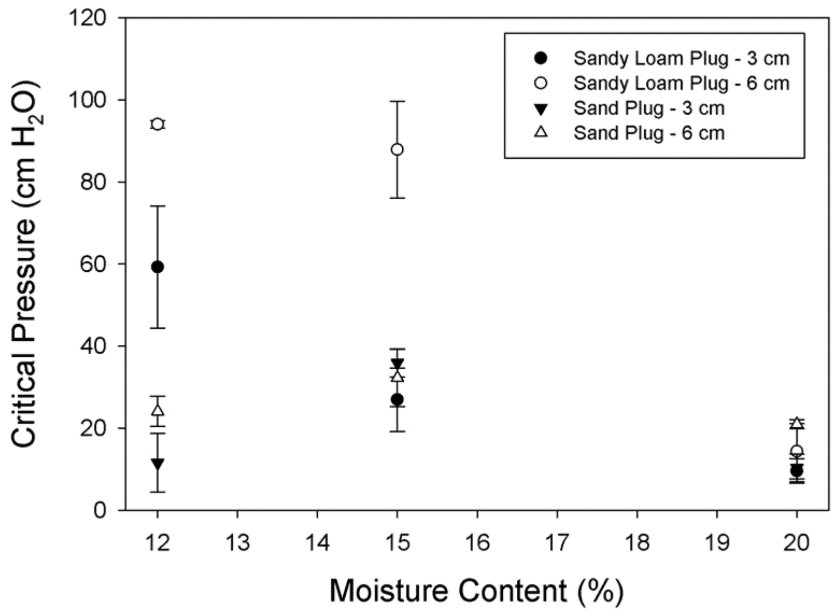

Figure 13. Critical pressure as it relates to moisture content, characterized by soil type and plug length. Maximum available pressure was 95 cm H_2O; after this point the pressure could no longer increase and the removal became time dependent.

A three-way ANOVA was run on the dataset for increasing moisture content at packing. The response variable was the maximum pressure achieved by the plug before removal. The factors were packing moisture, soil type, and plug length. The general linear model showed that all of our factors and interactions were significant at $\alpha=0.05$, meaning that all slopes and intercepts of our equations were significantly different. Tukey's pairwise comparisons show that the mean maximum pressures for 12% and 15% packing moisture were not significantly different from one another, but the mean maximum pressure for 20 % packing moisture was significantly different from the other two (Fig. 14). The mean maximum pressures were significantly different for the two soil types (Fig. 15), and the mean maximum pressures were significantly different for the two plug lengths (Fig. 16).

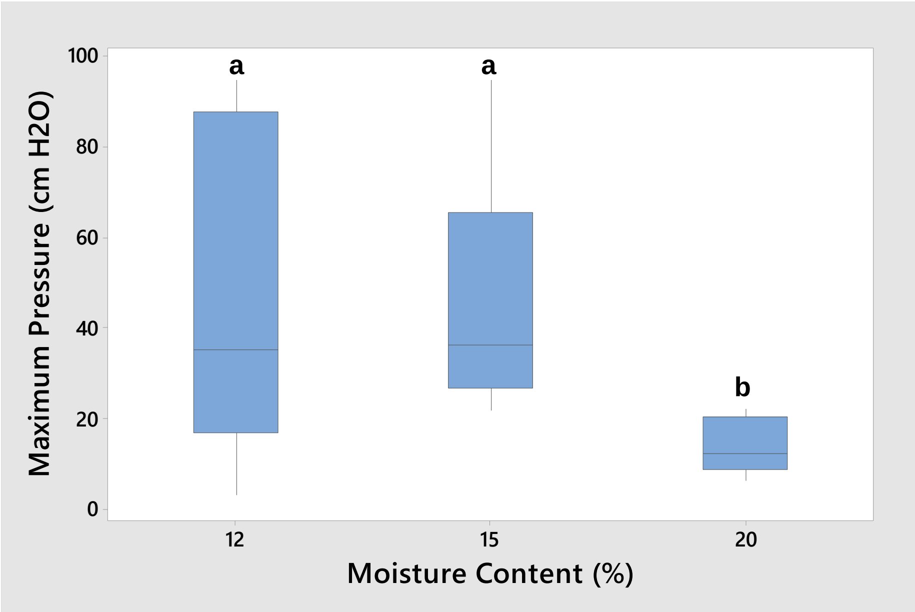

Figure 14. Tukey's pairwise comparisons of packing moisture content to maximum pressure from the three-way ANOVA. Means that do not share a letter are significantly different at α=0.05.

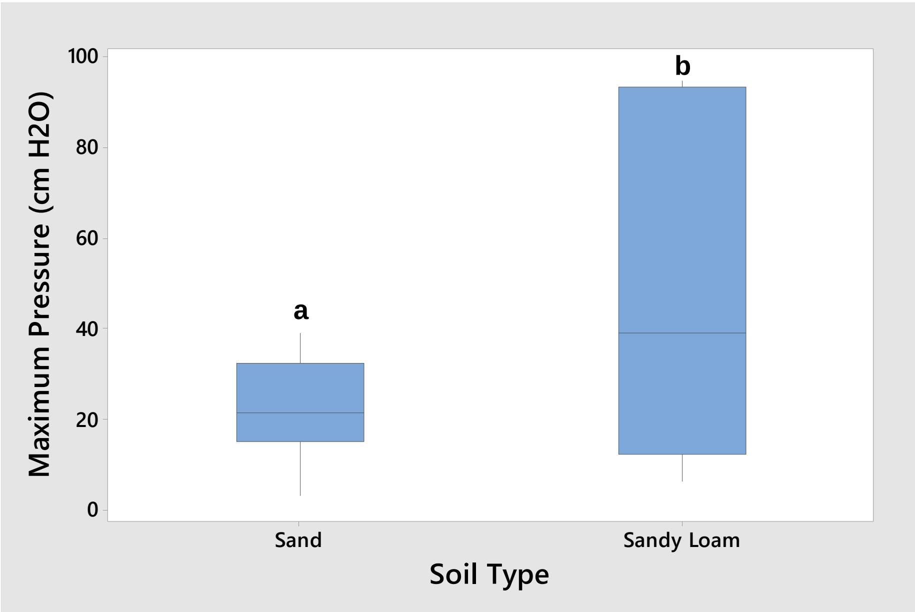

Figure 15. Tukey's pairwise comparisons of soil type to maximum pressure from the three-way ANOVA. Means that do not share a letter are significantly different at α=0.05.

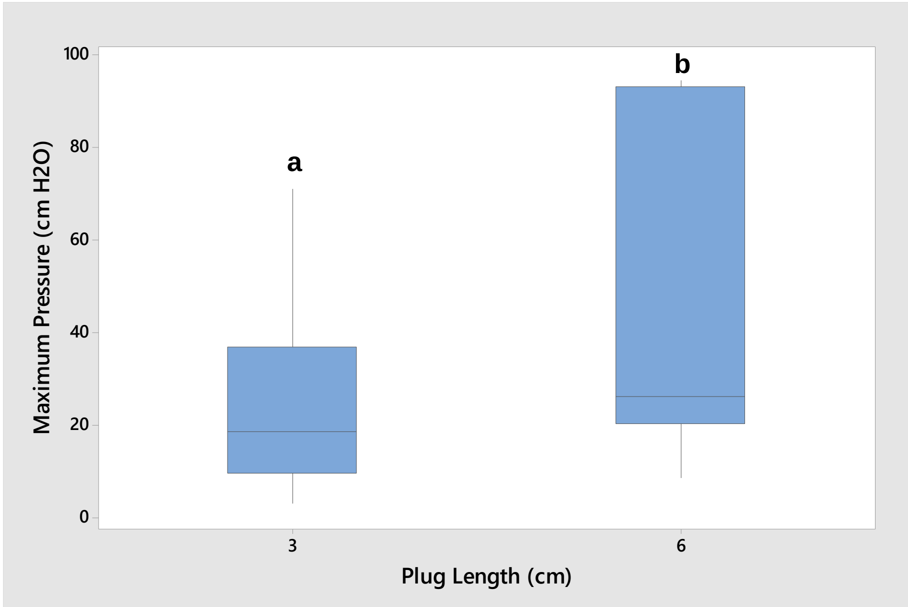

Figure 16. Tukey's pairwise comparisons of plug length to maximum pressure from the three-way ANOVA. Means that do not share a letter are significantly different at α=0.05.

Main effects and interactions plots were created for the factors of this three-way ANOVA. These figures show how all of the factors work together to explain the differences in the means of the maximum pressure needed for plug removal. The main effects plot showed that increasing moisture content resulted in decreased maximum pressure required for plug removal, that increasing length increased maximum pressure requirements, and that changing soil type from sand to sandy loam increased the maximum pressure requirement (Fig. 17). The interactions plot showed the differences in slope and intercept among the factors displayed (Fig. 18). Changes in slope and intercept showed significant differences between factors. These plots reinforced the idea that 12% and 15% packing moisture contents were not significantly different, but 20% packing moisture required significantly lower pressures for removal. They also showed that sandy loam plugs required more pressure for removal than sand plugs, and 6 cm plugs required higher pressures for removal than 3 cm plugs.

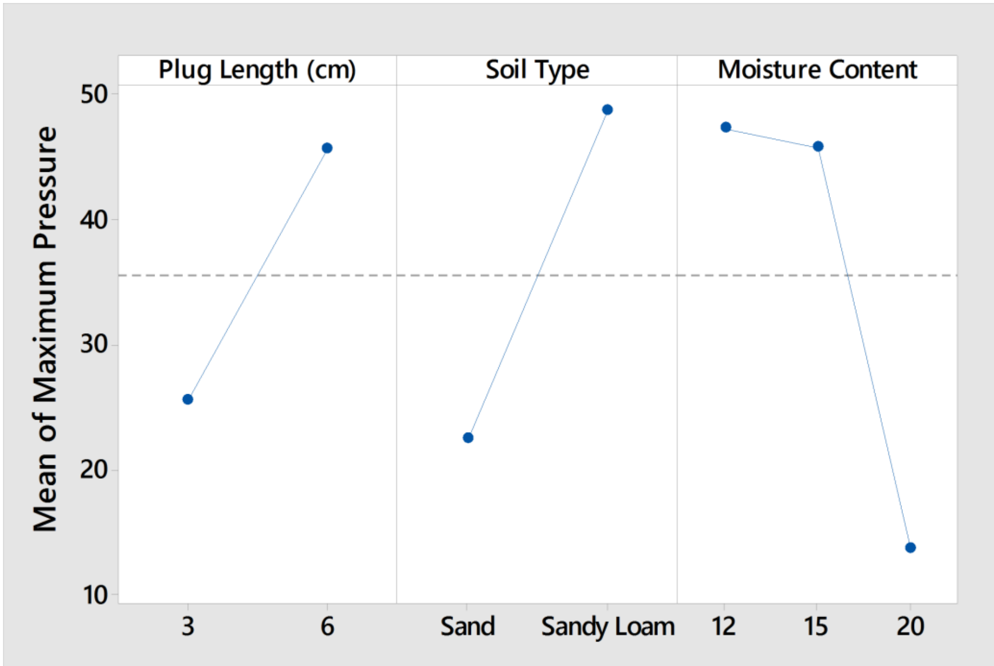

Figure 17. Main effects plot from the three-way ANOVA. Response variable is maximum pressure, explanatory variables are packing moisture content, soil type, and plug length.

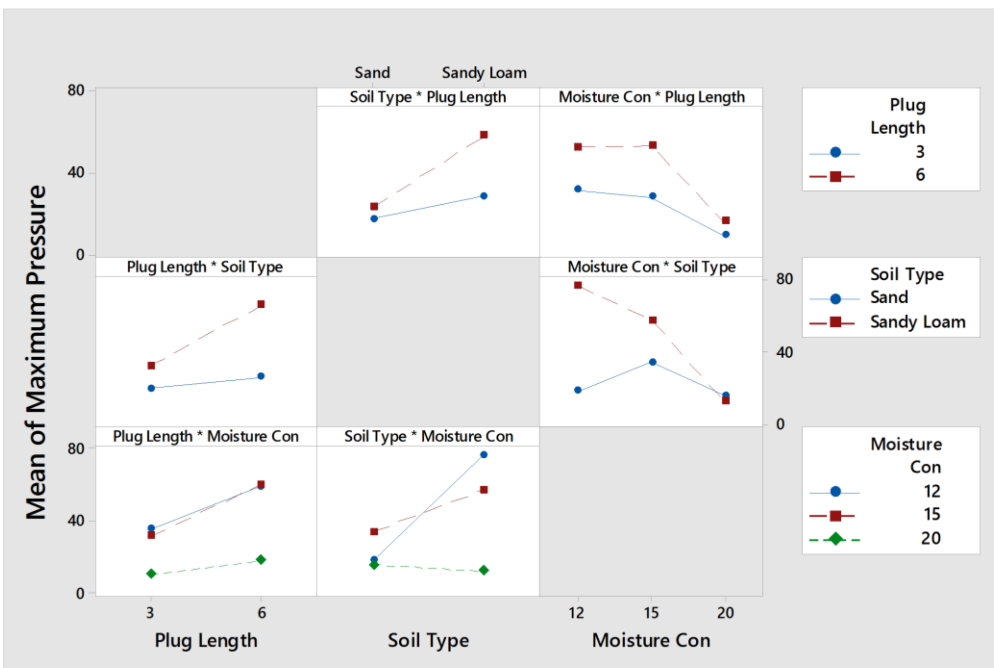

Figure 18. Interaction plot from the three-way ANOVA. Response variable is maximum pressure, explanatory variables are packing moisture content, soil type, and plug length.

When graphed directly from collected data, a trend of increasing critical pressures for plug removal can be seen clearly for the sandy loam soil, and a slight increase can be seen for the sand soil (Fig. 19). The sand plugs experienced less increase in critical pressure with increase in bulk density, and all plugs were removed with less than 30 cm of water. The sandy loam plugs experienced a noticeable increase in critical pressure by adding bulk density. With the wetting front being a key factor in plug removal, these results follow what was expected based on saturated hydraulic conductivity: as bulk density was increased, the conductivity of the soil decreased, causing the water to move through the soil at a slower rate and requiring a higher pressure for removal. These plugs were all packed at 12% moisture content. The maximum pressure that could be achieved was 95 cm H_2O. The 6 cm, 1.6 g cm^{-3} bulk density, sandy loam plug exceeded the maximum possible pressure; thus, critical pressure was more than that plotted in the graph, and this was why the variation was small for this experimental condition. For more cohesive soils at bulk densities greater than 1.5 g cm^{-3}, critical pressures may be quite large for plug removal.

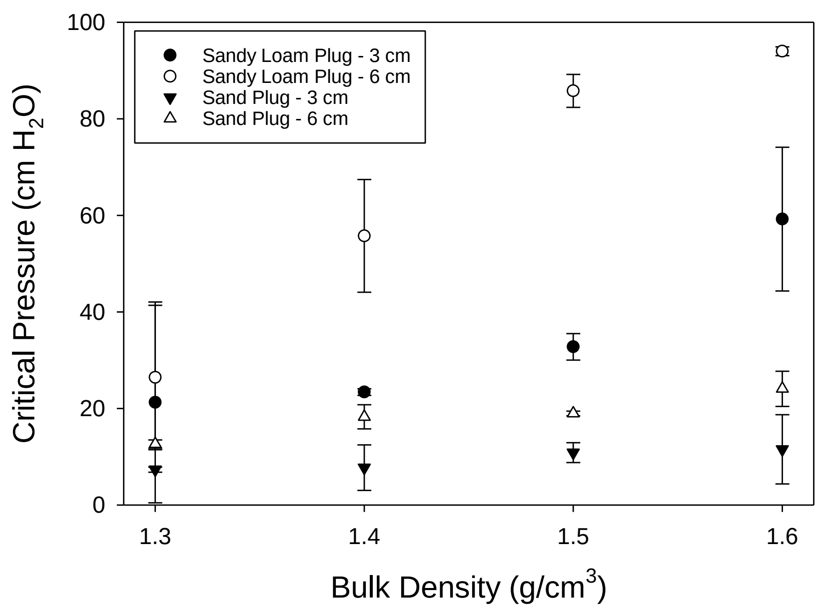

Figure 19. Critical pressure as it relates to bulk density, characterized by soil type and plug length. Maximum available pressure was 95 cm H_2O; after this point the pressure could no longer increase and the removal became time dependent.

A three-way ANOVA was run on the dataset for increasing bulk density. The response variable was the maximum pressure achieved by the plug before removal. The factors were bulk density, soil type, and plug length. The general linear model showed that all of our factors and interactions were significant at $\alpha=0.05$, meaning that all slopes and intercepts of our equations were significantly different. Tukey's pairwise comparisons show that the mean maximum pressures across all bulk densities were significantly different from one another (Fig. 20), the mean maximum pressures were significantly different for the two soil types (Fig. 21), and the mean maximum pressures were significantly different for the two plug lengths (Fig. 22).

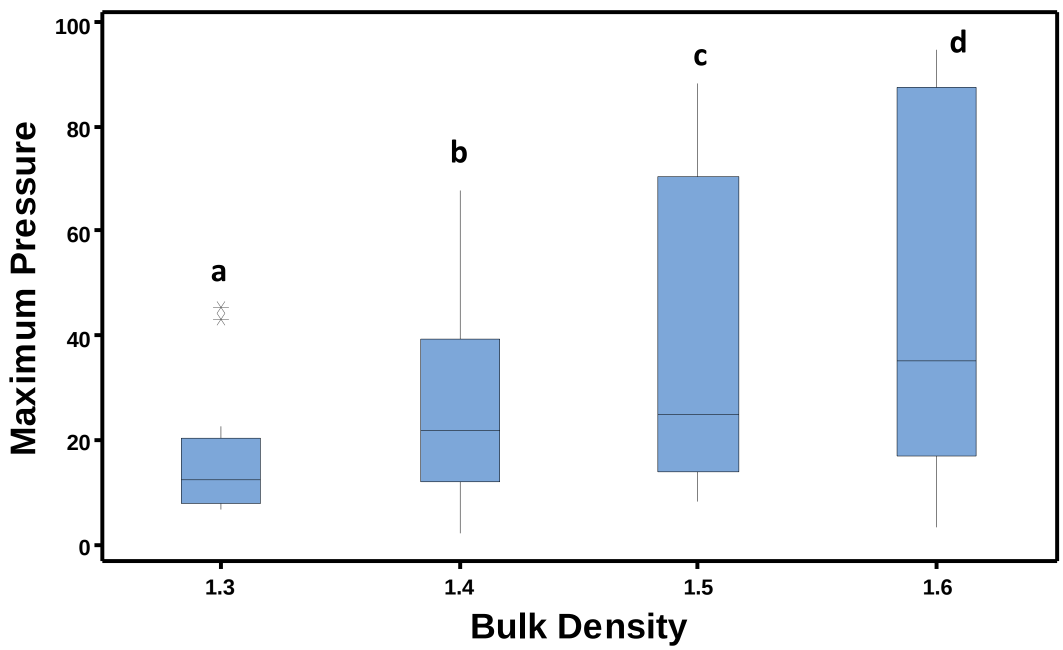

Figure 20. Tukey's pairwise comparisons of bulk density to maximum pressure from the three-way ANOVA. Means that do not share a letter are significantly different at α=0.05.

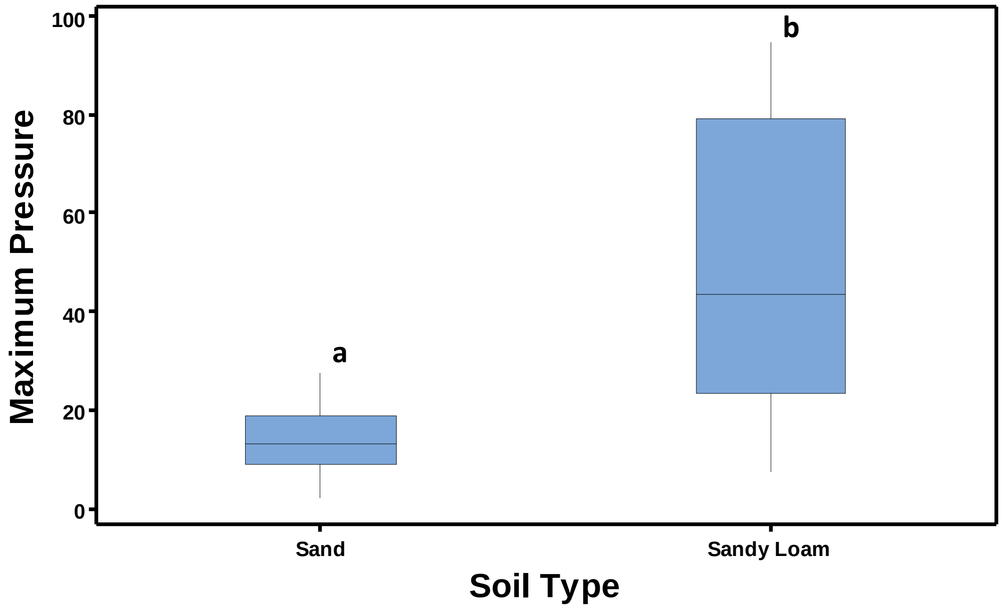

Figure 21. Tukey's pairwise comparisons of soil type to maximum pressure from the three-way ANOVA. Means that do not share a letter are significantly different at α=0.05.

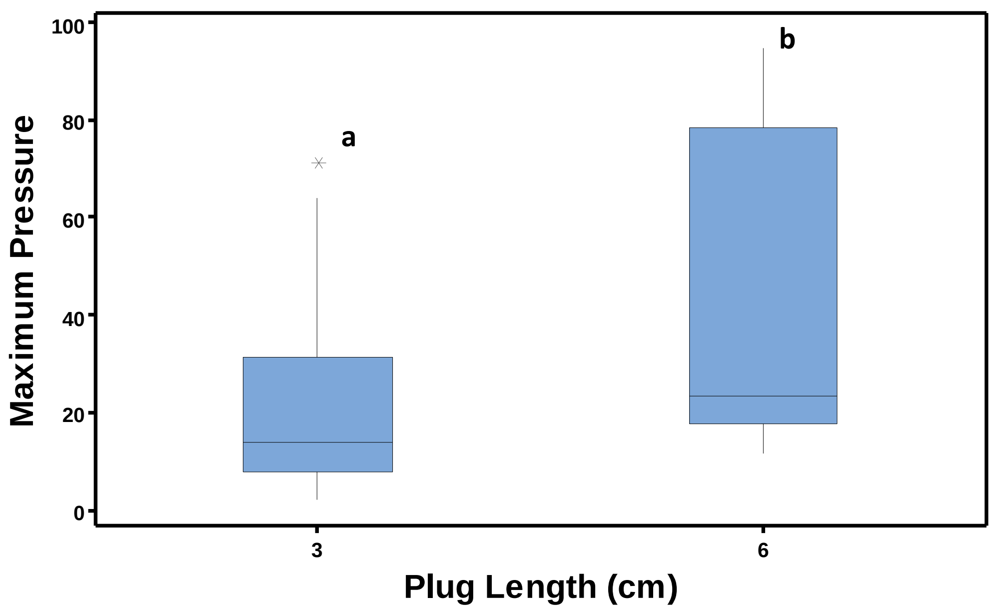

Figure 22. Tukey's pairwise comparisons of plug length to maximum pressure from the three-way ANOVA. Means that do not share a letter are significantly different at α=0.05.

Main effects and interactions plots were created for the factors of the three-way ANOVA. These figures show how all of the factors work together to explain the differences in the means of the maximum pressure needed for plug removal. The main effects plot showed that increasing bulk density resulted in increased maximum pressure required for plug removal (Fig. 23). It took higher pressures to remove 6 cm plugs than 3 cm plugs, and also more pressure was required to remove sandy loam plugs than sand plugs. The interactions plot showed the differences in slope and intercept among the factors displayed (Fig. 24). The bottom center graph of soil type*plug length showed a steeper slope for the 6 cm plugs than the 3 cm plugs. This tells us that adding plug length resulted in the need for a greater change in maximum pressures for the longer plugs to be removed as you move from sand to sandy loam soils. Similarly, the right center graph showed a different slope and intercept for the different soil types. There was a steeper slope for the more cohesive sandy loam soil than that of the sand, and the intercept for the sandy loam was higher than that of the sand. This showed that higher pressures were required for sandy loam plugs to be removed, and also that the sandy loam plugs required a greater pressure change as you moved from 3 cm to 6 cm plugs than the sand plugs. These results were likely due to the cohesive strengths of the soils: the more cohesive soil required higher pressures for removal.

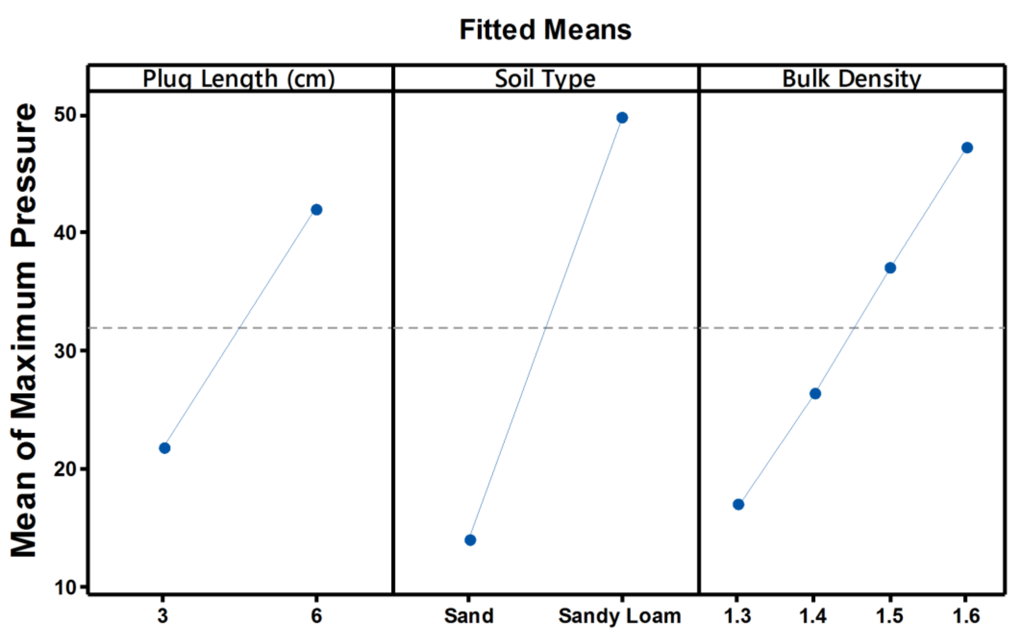

Figure 23. Main effects plot from the three-way ANOVA. Response variable is maximum pressure, explanatory variables are bulk density, soil type, and plug length.

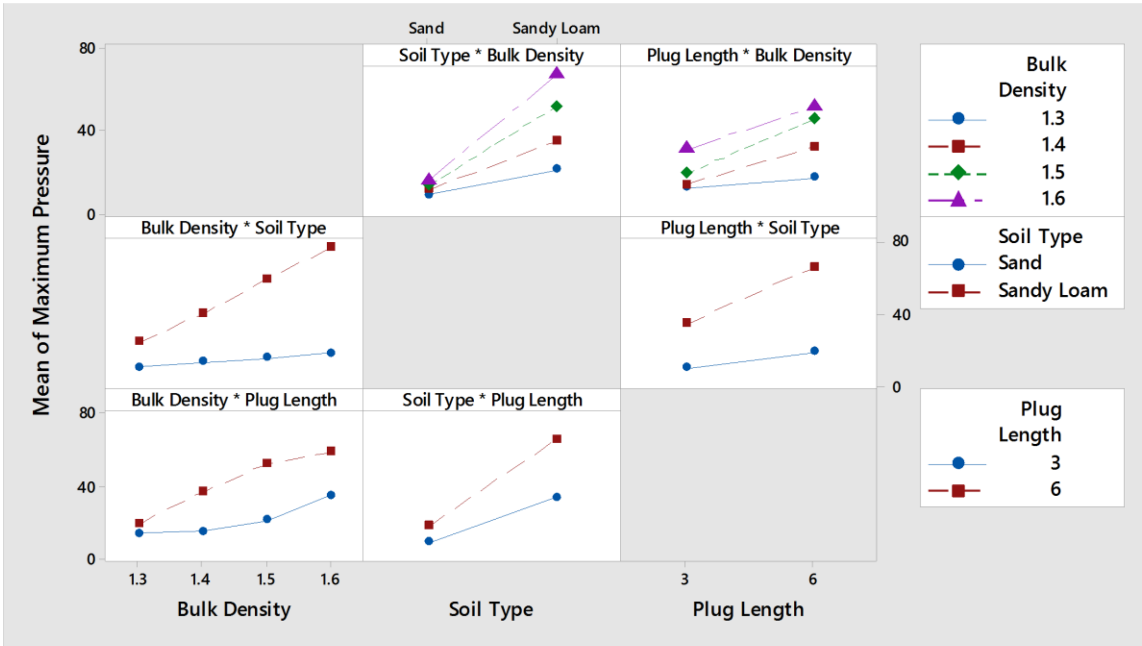

Figure 24. Interaction plot from the three-way ANOVA. Response variable is maximum pressure, explanatory variables are bulk density, soil type, and plug length.

Due to the 6 cm sandy loam data that reached the maximum possible applied head and then became dependent on time for removal, a three-way ANCOVA was run with time as a covariate. All four-way and three-way interactions were insignificant as were the bulk density*plug length and soil type*plug length interactions. The final model included plug length, soil type, bulk density, bulk density*soil type, time, time*bulk density, time*soil type, and time*plug length as significant intercepts and slopes at α=0.05. Tukey's pairwise comparisons showed that the mean maximum pressures were the same for bulk densities ranging from 1.3 to 1.5 g cm^{-3}, but different for 1.6 g cm^{-3} (Fig. 25), the mean maximum pressures were not significantly different for the two soil types (Fig. 26), and the mean maximum pressures were significantly different for the two plug lengths (Fig. 27). ANCOVA estimates means using equations rather than using the actual means like ANOVA, thus the means compared here were different than those above.

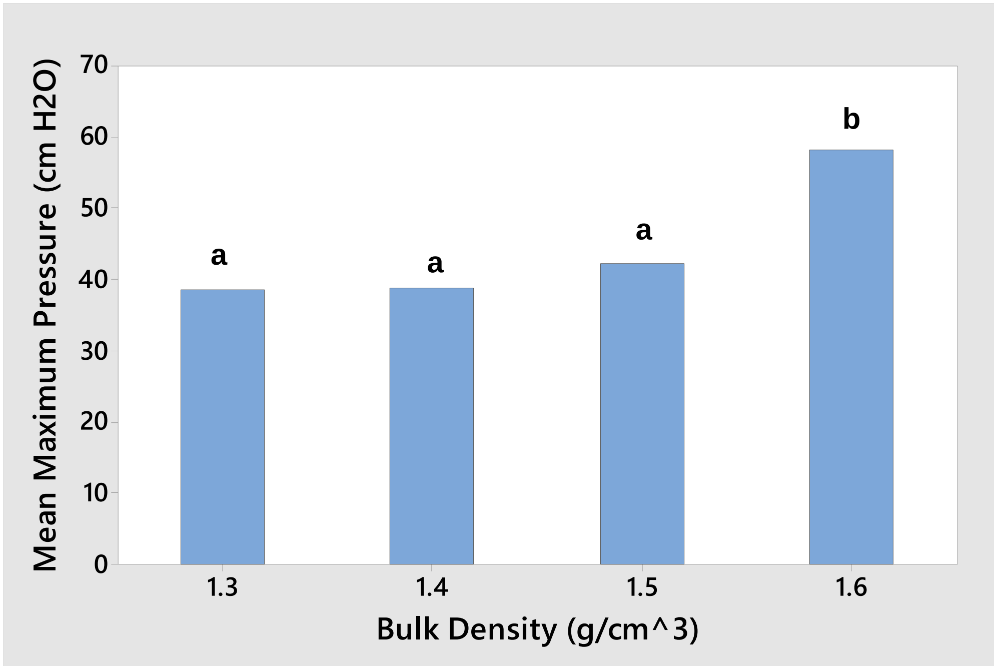

Figure 25. Tukey's pairwise comparisons of bulk density to maximum pressure from the three-way ANCOVA. Means that do not share a letter are significantly different at α=0.05.

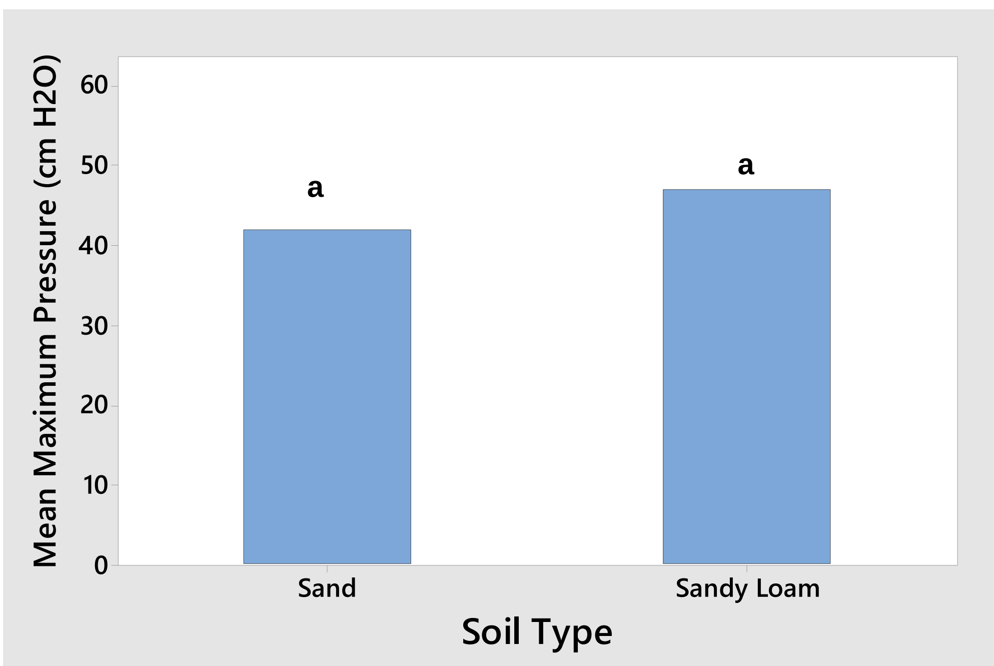

Figure 26. Tukey's pairwise comparisons of soil type to maximum pressure from the three-way ANCOVA. Means that do not share a letter are significantly different at α=0.05.

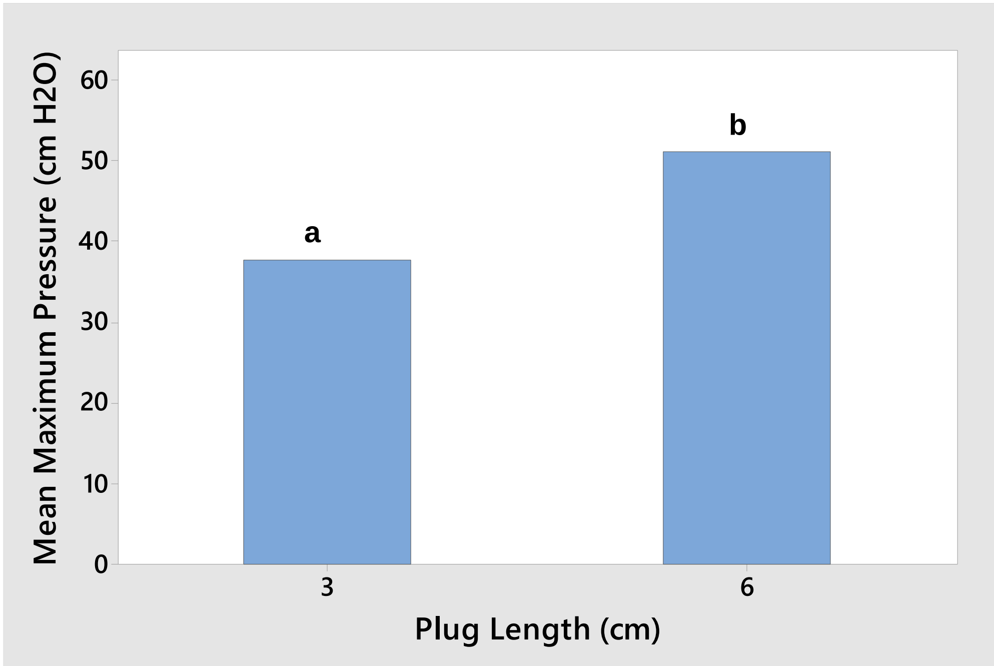

Figure 27. Tukey's pairwise comparisons of plug length to maximum pressure from the three-way ANCOVA. Means that do not share a letter are significantly different at α=0.05.

Main effects and interactions plots were created for the factors of the three-way ANCOVA. In the three-way ANOVA, the results matched intuitively the underlying processes. Once time was added as a covariate, the resulted become unexpected and difficult to explain. The main effects plot showed that increasing bulk density resulted in a decrease in maximum pressure required for plug removal initially with a sharp increase in pressure requirement for a bulk density of 1.6 g cm^{-3} (Fig. 28). The soil type had a much less steep slope than that seen in the ANOVA plots. The plug length plot was similar to that seen in the ANOVA. The interactions plot showed that there were different slopes and intercepts among the lines displayed (Fig. 29). There were fewer interactions displayed, because fewer interactions were significant to this model. Only the bulk density*soil type interaction was included because the other significant interactions were with the covariate (time). In the interaction plot sand showed a decrease in maximum pressure as bulk density increased. This was intuitively backwards from what was expected, and from what was observed in the ANOVA analysis. The sandy loam soil took on a u-shape as the bulk density increased first causing a slight decrease in maximum pressure then sharply increased as the bulk density approached 1.6 g cm^{-3}. The results of the three-way ANCOVA with time as a covariate provided interesting results that could indicate other unknown underlying processes at work within the plug.

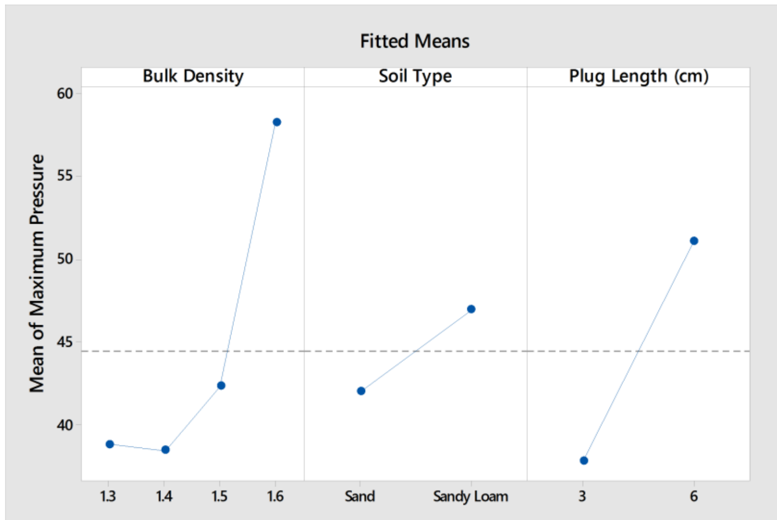

Figure 28. Main effects plot from the three-way ANCOVA. Response variable is maximum pressure, explanatory variables are bulk density, soil type, and plug length.

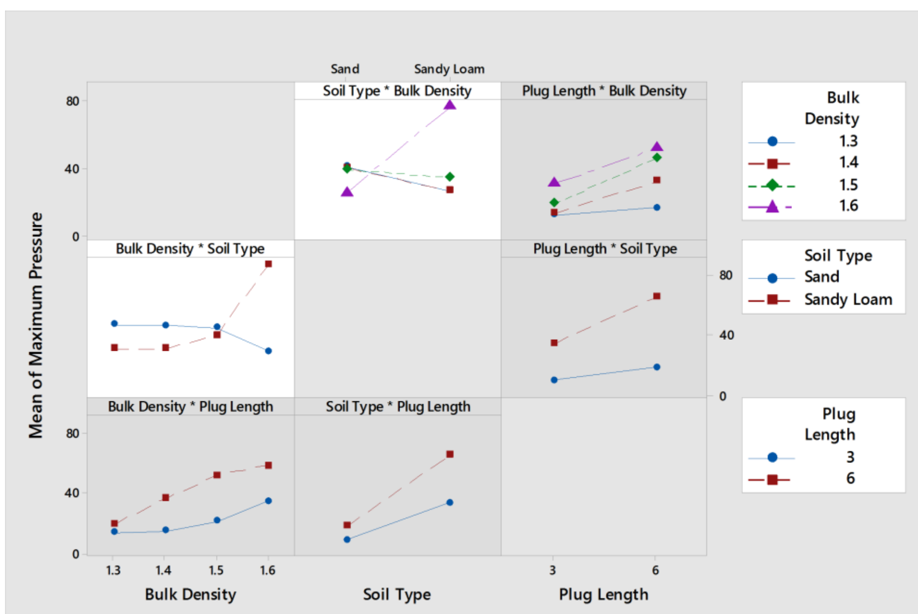

Figure 29. Interaction plot from the three-way ANCOVA. Response variable is maximum pressure, explanatory variables are bulk density, soil type, and plug length. Plots with gray backgrounds were not included in the model.

Pipe diameter was the final variable changed for dynamic head experiments. These experiments used clogs that were all packed at 1.6 g cm^{-3} bulk density and 12% moisture content. The sand 6 cm plug had significant differences due to pipe diameter at α=0.05; all others were not significantly different (Fig. 30). The p-values were obtained using two-tailed t-tests. An interesting result was that the sand showed a slight increase in required pressure in the larger pipe diameter, while the sandy loam plugs appeared to require lower forces for removal in the larger diameter. The surface area to volume ration was less in the larger pipe, and there was also a larger area that the pressure was acting over. Intuitively, it would seem that the larger diameter should require lower removal pressures than the smaller diameter; however, the added mass of the sand in the larger diameter could be counteracting this, thus resulting in the larger pressures observed.

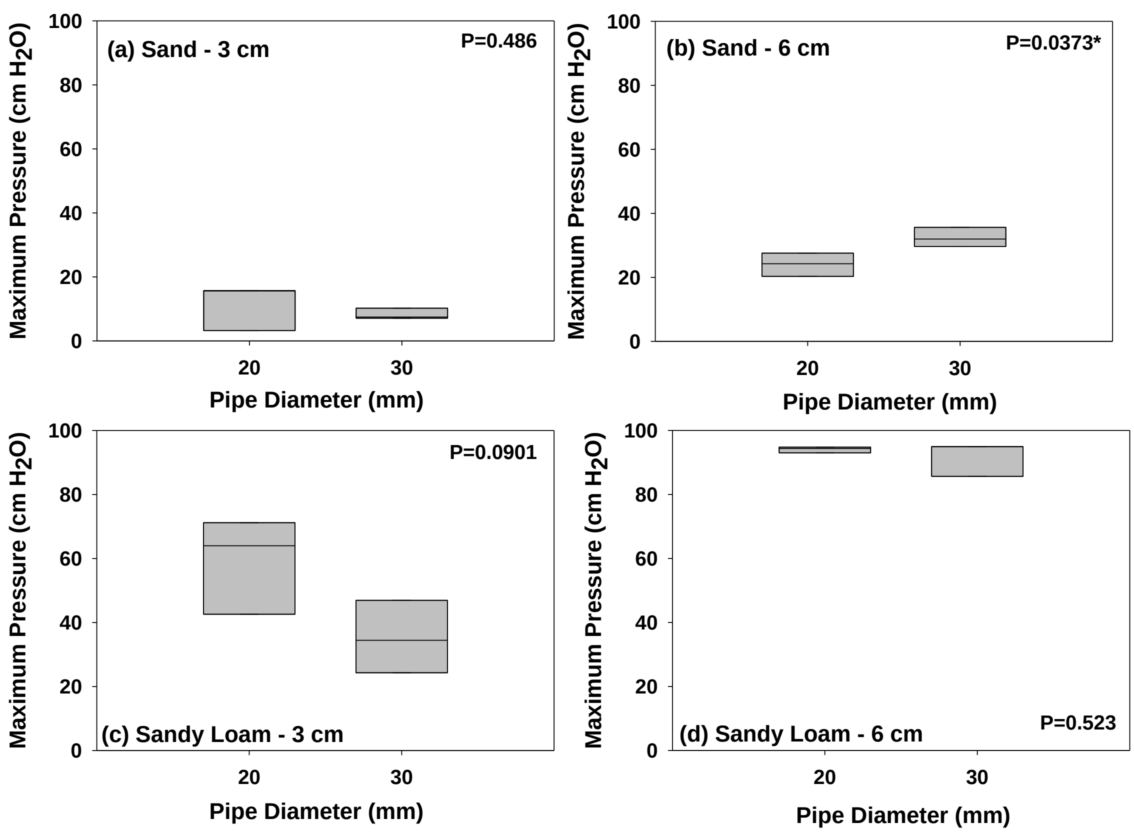

Figure 30. Increasing the pipe diameter resulted in a decrease in critical pressure for all plug lengths and soil types.

Constant Head Experiments

All plugs were removed intact, and approached saturation before removal. Some plugs never sustained the applied constant head and were therefore removed instantaneously by the initial burst of pressure, such as the sand experiment shown below (Fig. 31a). Some plugs withstood the applied head for long periods of time; Figure 18b shows a plug that remained in place for over 500 s. Some plugs took hours before removal. Typically there was an instantaneous spike in pressure up to the applied head if the plug was not removed from the burst. It then held the pressure until the critical time was reached at which time the plug was removed and the pressure dropped off quickly.

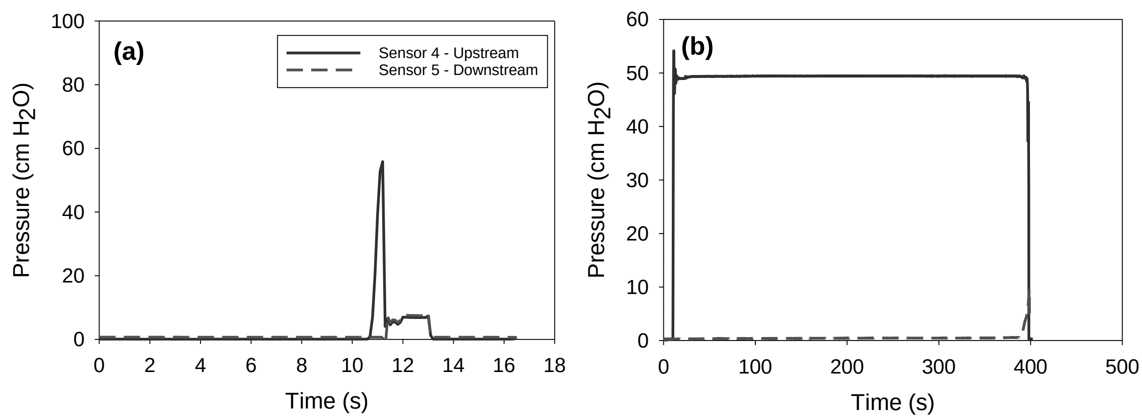

Figure 31. Example outputs from pressure transducers for a) Sand, 1.6 g cm^{-3} bulk density, 12% moisture content, and 3 cm length, at 100 cm applied head and b) Sandy loam soil, 1.6 g cm^{-3} bulk density, 12% moisture content, and 6 cm length, at 50 cm applied head. The sand plug never reached the applied head and was removed nearly instantaneously upon the pressure being applied. The sandy loam soil withstood the applied pressure for more than 500 seconds before it was removed.

Increasing the bulk density of plugs increased the critical time (time pressure was applied before clog removal) (Fig. 32). This follows the same pattern as the hydraulic conductivity, as the bulk density increased the hydraulic conductivity decreased slowing the wetting front. All sand plugs were removed in under 100 s, while the sandy loam plugs ranged from less than 10 s to near 1000 s. These values translated well to the saturated hydraulic conductivity values with sand having an extremely high conductivity and lower conductivities for the sandy loam. An increase in the length of the plug increased the critical time. Note that the figures are on a semi-logarithmic scale. There was an exponential relationship between bulk density and critical time. As bulk density increased, critical time increased exponentially. This relationship was demonstrated by the more cohesive sandy loam soil. The sand was more difficult to pack at the lower bulk densities. The 1.2 and 1.3 g cm^{-3} bulk densities may have been less homogeneously packed, which accounted for the deviation of the relationship at those densities as well as the increased variation between experiments.

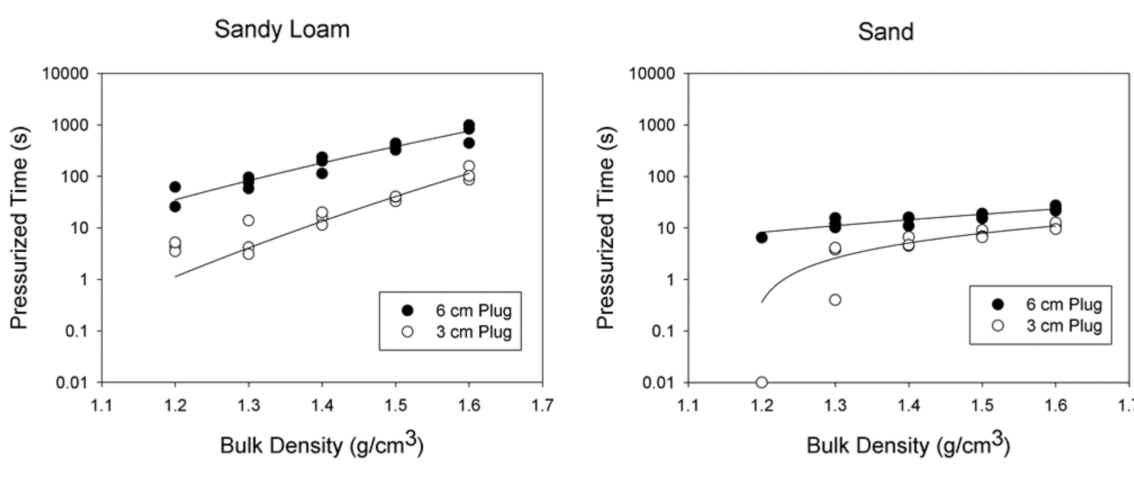

Figure 32. Pressurized time (critical time) as it relates to bulk density for sandy loam soil and sand at 3 cm and 6 cm plug lengths. Graphs are semi-log plots and show an exponential relationship. 6 cm plugs take less time to remove than 3 cm plugs. As bulk density increases, the critical time increases exponentially.

Increasing the applied constant head resulted in a decrease in pressurized time (Fig. 33). Semi-logarithmic plots indicated a negative exponential relationship: as constant head increased, the time until plug removal decreased exponentially. Pipe roughness did not have a significant effect on sand plugs, which were all removed in under 100 s. Adding roughness to the pipe for the sandy loam soil increased the plug removal time by as much as 50%. For the soil plugs, sand roughened pipes resulted in the highest pressurized times followed by sandy loam roughened and finally smooth pipe. The soil plug experiments ranged from less than 10 s to nearly 3 hours for removal. As expected, 6 cm plug lengths took longer to remove than 3 cm plugs.

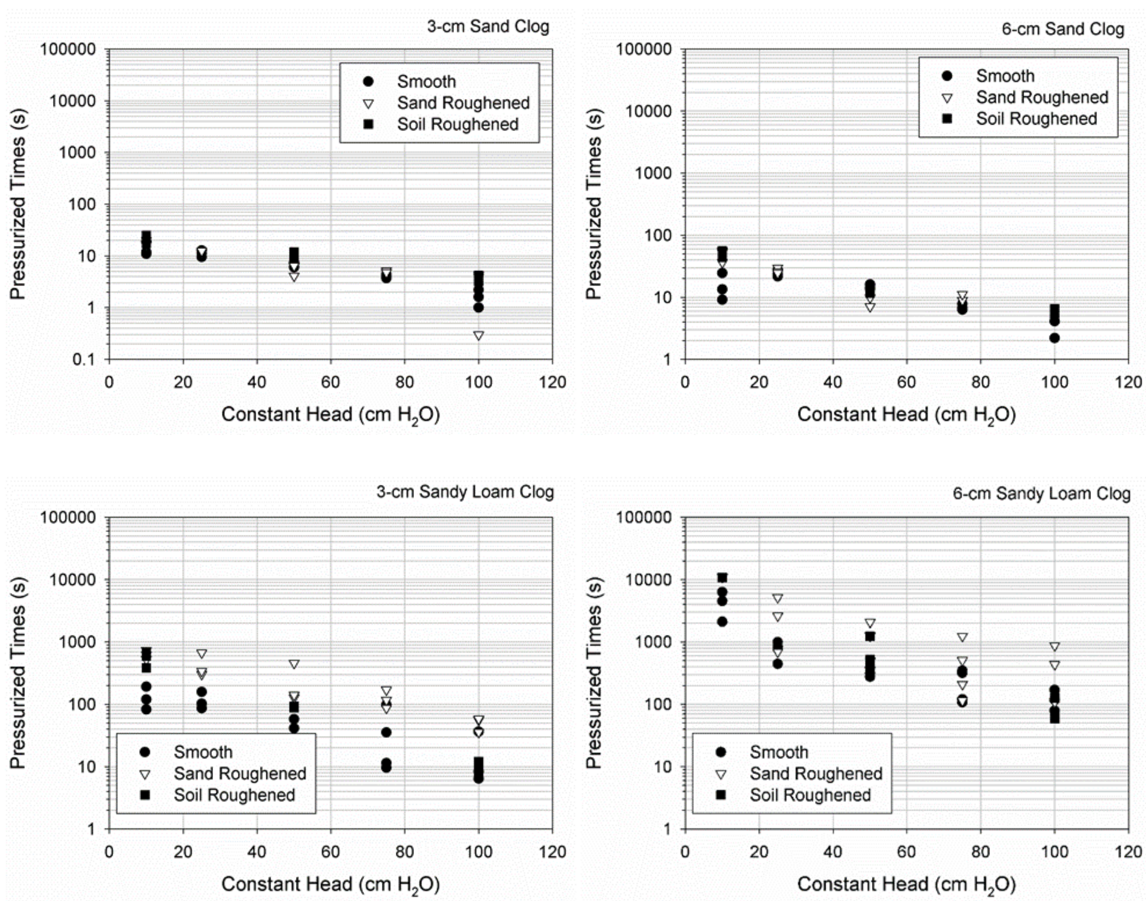

Figure 33. Pressurized time (critical time) as it relates to increasing applied constant heads and pipe roughness, divided into soil type and plug length.

Pipe diameter was the final variable changed for constant head experiments. All experimental plugs were packed to 1.6 g cm^{-3} bulk density and 12% moisture content. For all soil types and plug lengths, the larger diameter resulted in shorter pressurized times observed (Fig. 34). The difference in pressurized time was much greater for the sandy loam plugs than the sand plugs. Two-tailed t-tests or Mann-Whitney Rank Sum tests indicated that only the differences in the sandy loam pressurized times were statistically significant at a 95% confidence interval. This was likely due to the small values of pressurized time for the sand experiments. There was more variability among the smaller pipe diameter, most likely due to experimental differences and not significant to the results. The results from the dynamic head experiments for changing diameter did not experience the same variability.

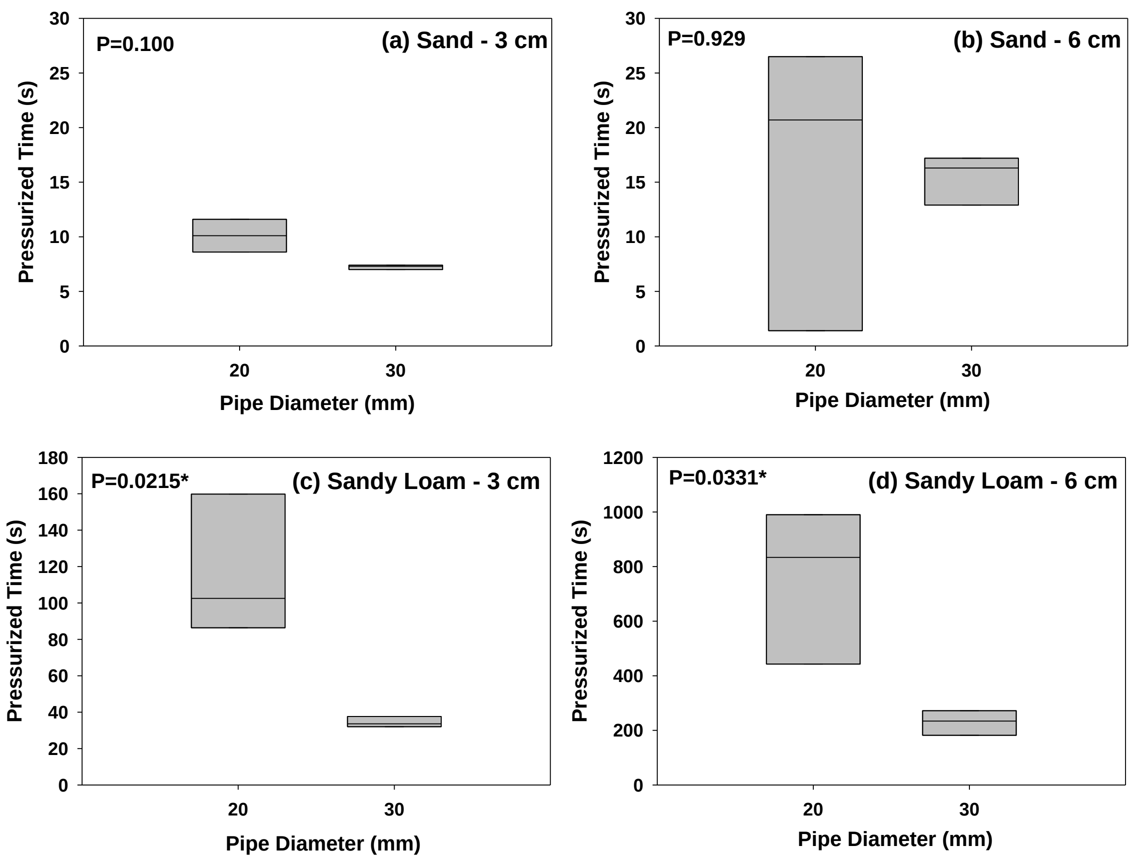

Figure 34. Increasing the pipe diameter resulted in a decrease in critical pressure for all plug lengths and soil types."*" indicates means that are significantly different at α=0.05.

Impulse Data

Comparison of Constant and Dynamic Experiments

Before these data were combined, they were first compared to determine if the differences between the constant and dynamic experiences were statistically significant. Data were graphed in box plots and either a two-tailed t-test or Mann-Whitney ranked sum test were performed, based on normality of the data, to determine whether the differences between the two were significant (Fig. 35). P values with a "*" had statistically significant differences that could not be attributed to random variance for a 95% confidence interval. The dataset selected for representation in the box plots had the most data, and all utilized the Mann-Whitney ranked sum test as these data did not meet the normality requirements. The dataset with the most available data was that of varying roughness. The results of the statistical analysis between dynamic and constant head for this data set are listed in Table 2.

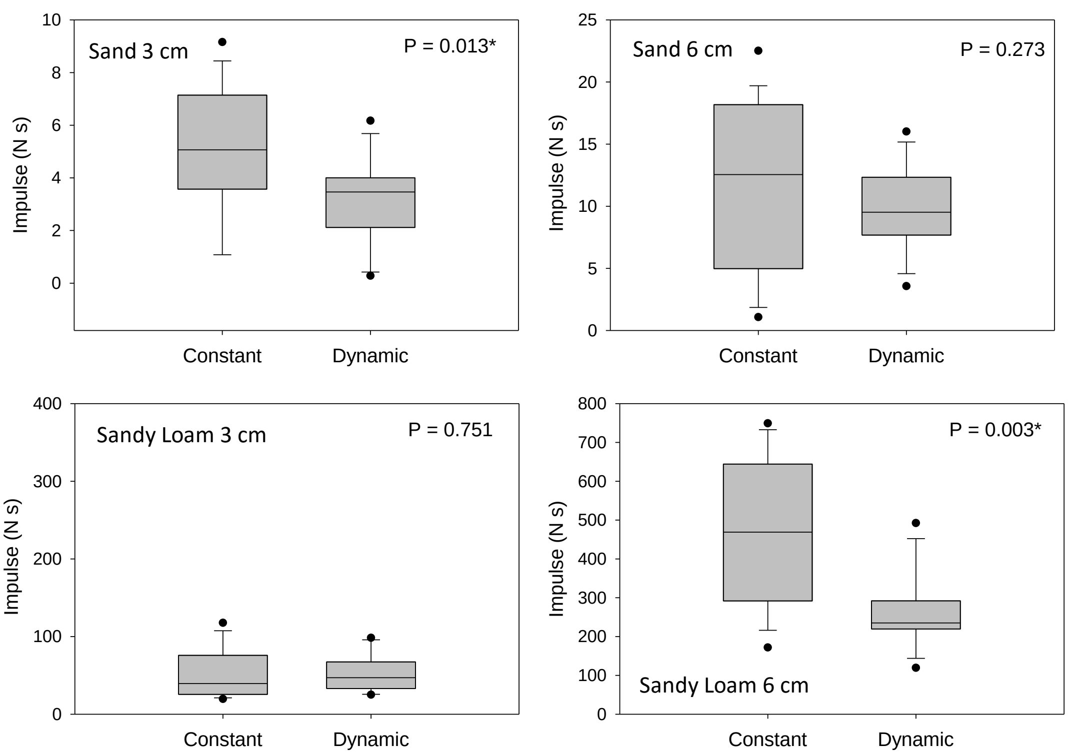

Figure 35. Comparison of constant and dynamic experiments. P-statistics for each are given to verify if the differences between the two are significant.

Table 2. Statistical tests for differences in dynamic and constant head experiments.

Soil Type	Plug Length	Experimental Variable	Statistical Test	p-value
Sand	3 cm	Smooth Pipe	Mann-Whitney Rank Sum	0.013*
		Sandy Loam Roughened	Mann-Whitney Rank Sum	0.259
		Sand Roughened	Mann-Whitney Rank Sum	0.301
	6 cm	Smooth Pipe	Mann-Whitney Rank Sum	0.273
		Sandy Loam Roughened	Mann-Whitney Rank Sum	0.726
		Sand Roughened	Two-tailed t-Test	0.475
Sandy Loam	3 cm	Smooth Pipe	Mann-Whitney Rank Sum	0.751
		Sandy Loam Roughened	Mann-Whitney Rank Sum	0.580
		Sand Roughened	Mann-Whitney Rank Sum	0.484
	6 cm	Smooth Pipe	Mann-Whitney Rank Sum	0.001*
		Sandy Loam Roughened	Mann-Whitney Rank Sum	0.953
		Sand Roughened	Two-tailed t-Test	0.625

"*" indicates p-values that are significantly different at α=0.05.

These figures and table showed that there was a range in which it was acceptable to combine data. Plugs that were easiest to remove and those that were hardest to remove had differences that were larger than would be expected due to chance. It would appear that only constant and dynamic data for those that are 6 cm sand plugs and 3 cm sandy loam plugs could be combined. Arguably, you could also combine data for the 3 cm sand plugs, because when graphed on the same scale as the 6 cm sandy loam plugs the differences could not be seen due to the small impulse values rendering the difference negligible. The lack of difference between dynamic and constant head experiments on plugs that were more easily removed was likely due to the rate at which these plugs approached saturation. The sand plugs had a high enough hydraulic conductivity that the pressure differences were less important in the constant and dynamic head experiments. The small length of the 3 cm sandy loam plugs allowed for a shorter saturation time, which was small enough that the differences in dynamic and constant head experiments were not significant. In experiments where the plug was more cohesive and had a greater length, there was more to the story and the constant and dynamic experiments were no longer comparable. These differences follow Darcy's equation for unsaturated flow:

$$q = -K(\theta)\frac{\partial h}{\partial z} \tag{6}$$

where q was the flux of water is moving into the unsaturated soil plug with units of length per time, $K(\theta)$ was the hydraulic conductivity of the soil which is a function of the water content (θ), h was the applied head, and z was the length of the plug. As water content increased, the hydraulic conductivity increased nonlinearly until it reached saturation (Fig. 36). In the constant head experiments, the head remained the same and the flow rate was dictated by changing conductivity with increased moisture content. In the dynamic head experiment, the head was increasing and reached higher pressures than the constant head experiments. This resulted in the water content increasing faster, increasing the conductivity to saturated hydraulic conductivity in less time. This nonlinear increase allowed for the dynamic experiments to be removed at lower

Imp than the constant head experiments. This was shown in the average *Imp* for dynamic head 6 cm sandy loam plugs being less than that of the constant head experiments. These figures also showed that the constant head experiments had more variability in *Imp* than the dynamic experiments. This variability is likely due to a large range of applied constant heads; the higher applied pressures resulted in smaller *Imp*, due to the faster rate of saturation. The smaller applied heads saturated at a slower rate. An interesting result was shown through adding roughness to the sandy loam 6 cm experiments, and the differences were no longer significant. Adding roughness should have caused the plug to require more *Imp* for removal, and since the relationship was nonlinear between time and pressure, it should have caused the constant head experiments to require even more *Imp* than the dynamic head experiments, causing the difference to be greater. One thing to note however, was that for this particular set of experiments, the dynamic experiments reached the maximum possible applied head and then became time-dependent constant head experiments. This result caused the dynamic and constant head experiments to be more similar and thus the two were no longer significantly different.

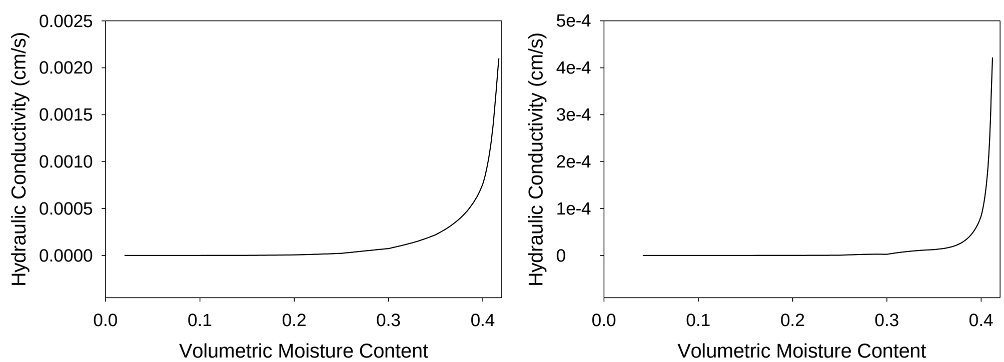

Figure 36. Hydraulic conductivity as it relates to water content of a sand (left) and sandy loam (right) soils. As water content increases, the hydraulic conductivity of the soil increases nonlinearly until it reaches saturation. Hydraulic conductivity values were found using van Genuchten's equations. Source: van Genuchten (1980).

In field scenarios it will be rare to see soil piping in sandy soils. This means that in field situations, it is important to consider the differences in *Imp* based on whether it is a constant head or a dynamic head process. It will be important to consider the hydraulics inside of the plug in order to determine removal *Imp* and slope stability.

Experimental Variable Comparisons with Impulse

Data that could be statistically combined were then analyzed based on experimental variable effects. For sand plugs and 3 cm sandy loam plugs, the constant and dynamic head experiments were combined and separated by experimental variable for comparison of how the variable affected *Imp*. The first variable that was observed was bulk density. Groups that were not statistically different share the same letter. Changing the bulk density had no effect on the sand experiments; there were no statistically significant differences in the means of the sand experiments of either length by changing the bulk density at packing (Fig. 37 and 38). This was likely the result of the high conductivity of the sand which allowed for extremely low removal *Imp*. Increased bulk density for the sandy loam 3 cm plugs resulted in greater *Imp* requirements for plug removal (Fig. 39). An increase in bulk density created a significant difference in the mean impulse required for removal for all except 1.5 and 1.6 g cm^{-3} bulk densities. The differences were likely due to the decreased hydraulic conductivity that results from soil compaction. In the Matthews et al. (2010) paper, there was an exponential relationship between soil compaction and conductivity of the soil. This relationship led to the saturation time being longer for plugs with higher compaction.

As has been stated, the wetting time had the largest impact on plug removal in this set of experiments; thus, removal at lower *Imp* for lower bulk densities was expected for sediments more cohesive than sand. It will be important to find out how plug formation impacts the bulk density of a plug in field situations to determine the flux through the plug and when plug removal will occur. Depending on plug formation mechanisms, internal erosion and deposition or pipe collapse, the plug could have similar bulk densities as the surrounding matrix or completely different bulk densities.

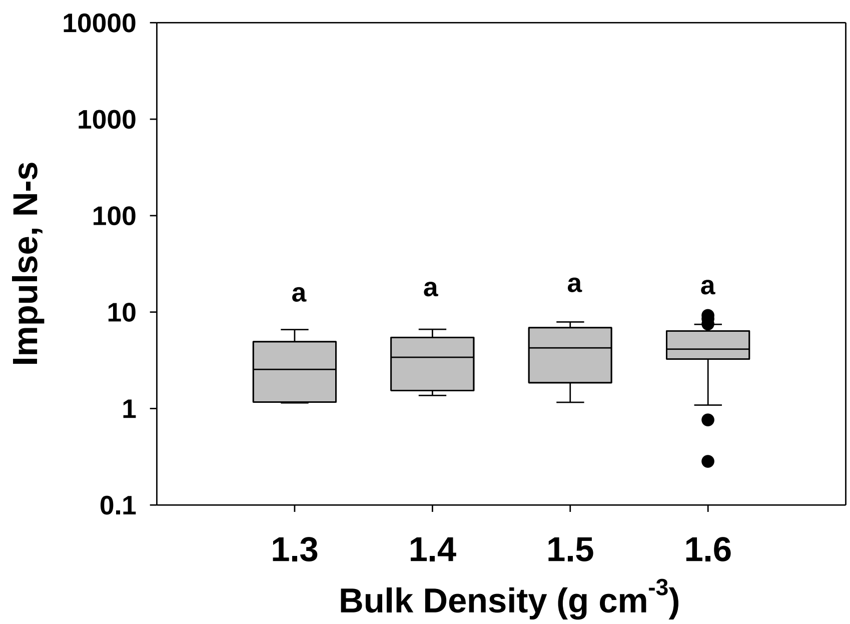

Figure 37. Sand 3 cm bulk density comparison. Means that do not share a letter are significantly different at α =0.05.

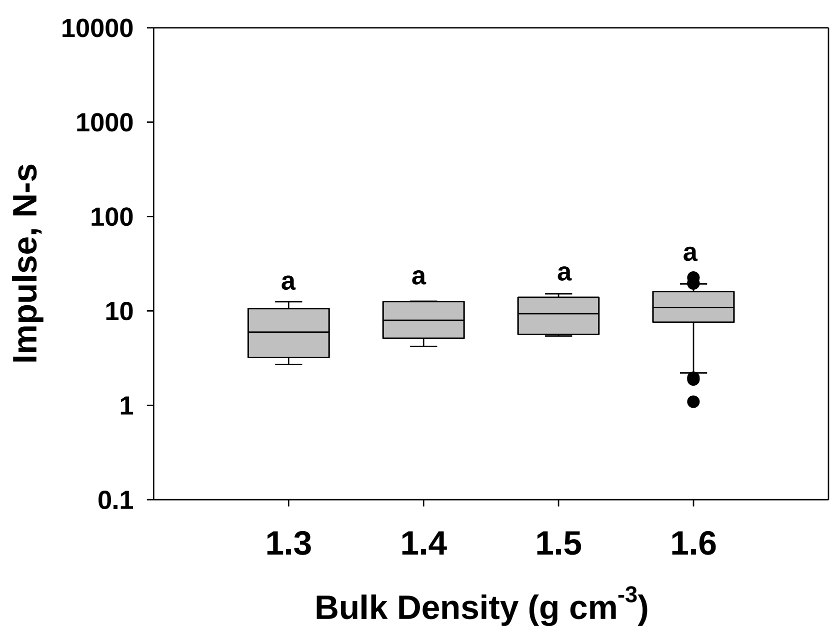

Figure 38. Sand 6 cm bulk density comparison. Means that do not share a letter are significantly different at α =0.05.

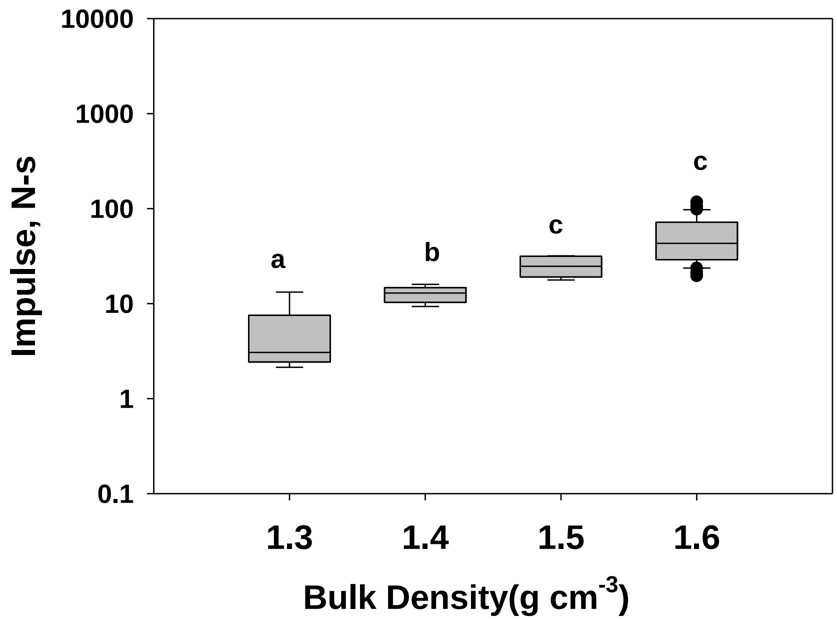

Figure 39. Sandy loam 3 cm bulk density comparison. Means that do not share a letter are significantly different at α =0.05.

The second variable that was compared using *Imp* was pipe roughness. Adding pipe roughness did not change the removal mechanism for the plugs and all plugs were removed intact. Adding roughness made it impossible to watch the wetting front inside of the plug to know if the plug was still saturating before removal. The sand was coarser than the sandy loam; therefore, the increasing order of roughness was smooth pipe, sandy loam roughened pipe, and sand roughened pipe. Differing letters implied a significant difference, a shared letter meant there was no significant difference between the mean *Imp* requirements for the roughness types. The sand 3 cm and 6 cm plugs showed a slight increase in *Imp* required for removal from adding roughness to the pipe (Fig. 40 and 41). There was no significant difference between the sandy loam and sand roughness types. With all of the *Imp* being low, there was a good chance that these differences were negligible. For the sandy loam 3 cm plugs, there was no significant difference between the average *Imp* required for removal in a smooth pipe and the average *Imp* required in a pipe roughened with sandy loam soil (Fig. 42). There was a significant difference between the sand roughened pipe and the other two roughness types. Examination of the figure showed that while significantly different, the values were still relatively close together. While roughness may have played a role in *Imp* required for removal, it did not play as significant a role as bulk density of the plug. In field examples of piping, the roughness will be determined by the soil matrix surrounding the soil pipe.

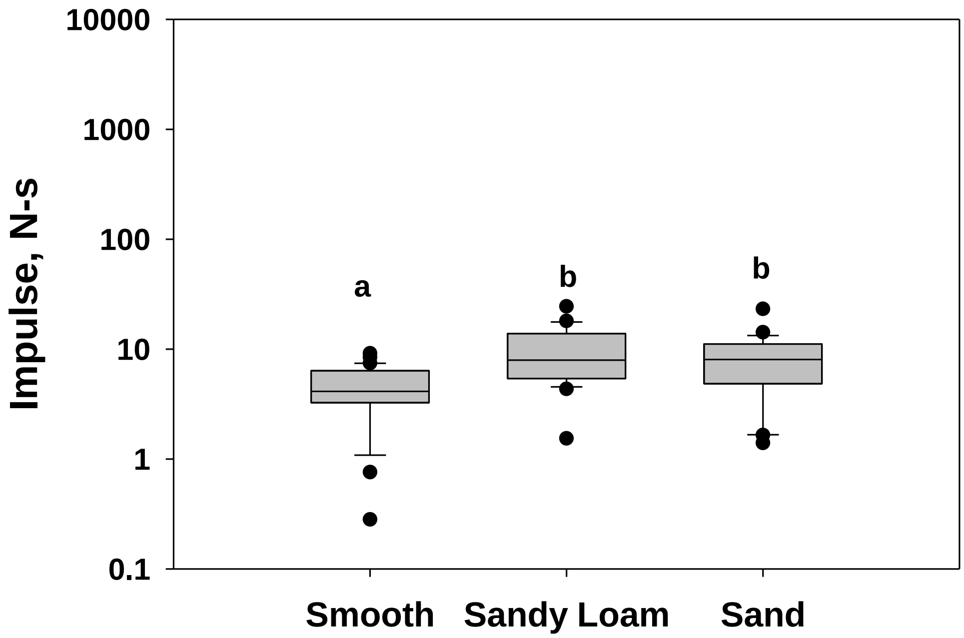

Figure 40. Sand 3 cm pipe roughness comparison. Means that do not share a letter are significantly different at α =0.05.

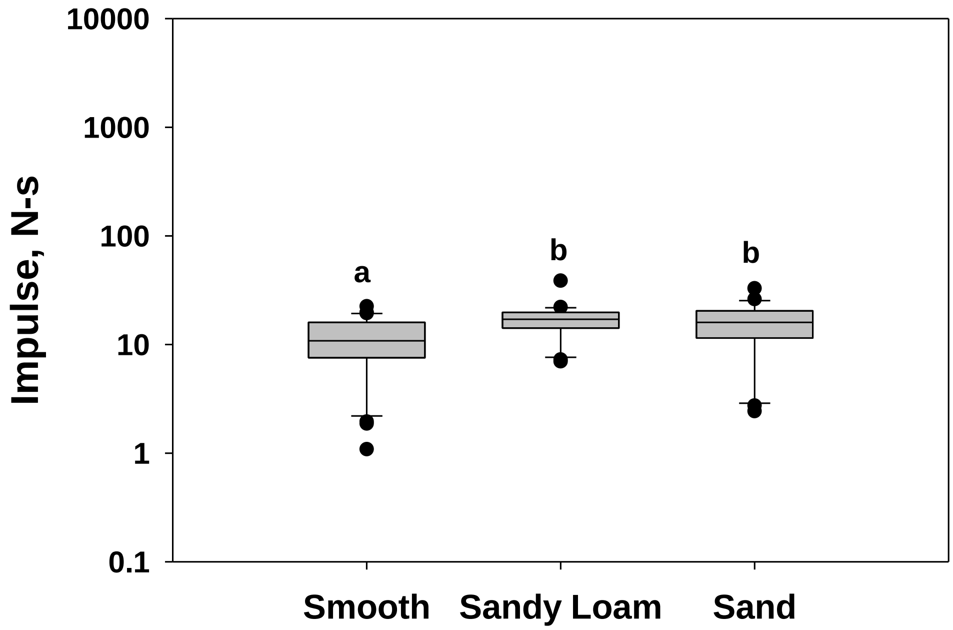

Figure 41. Sand 6 cm pipe roughness comparison. Means that do not share a letter are significantly different at α =0.05.

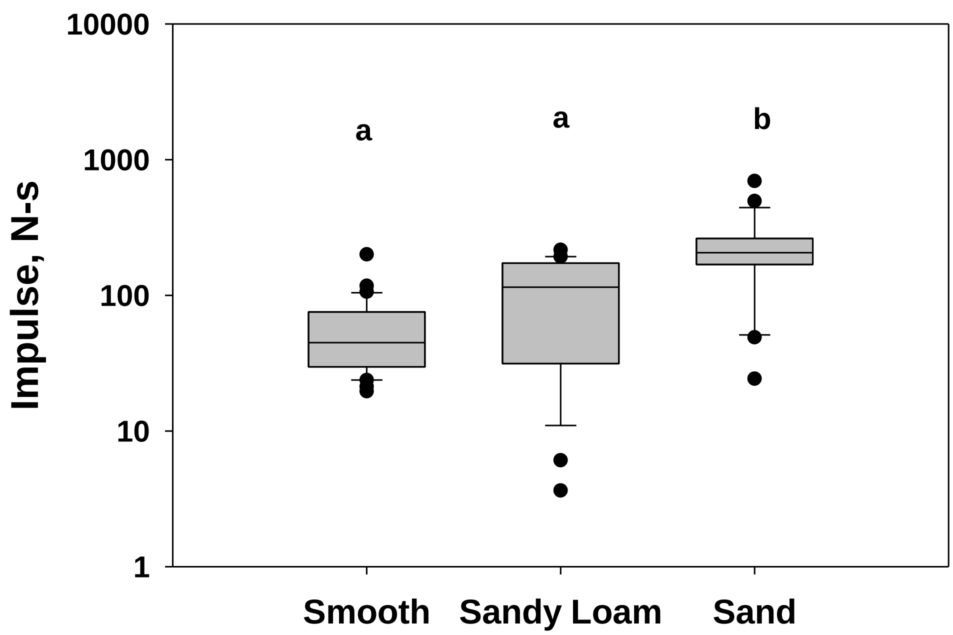

Figure 42. Sandy Loam 3 cm pipe roughness comparison. Means that do not share a letter are significantly different at α =0.05.

Wetting Front Migration Calculations

Observing the wetting front moving through the plug before removal led to the question of how the infiltration rate relates to the time of plug removal. This led to calculating the wetting front length as a percentage of total plug length at the time of plug removal. The sand plugs removed when the wetting front reached approximately 55% of the length of the clog (Fig. 43). The sandy loam plugs required a wetting front near 75% of the plug length for removal (Fig. 44). The slope of the observed versus predicted time graphs decreased as the wetting front moved across the plug length. The removal occurred when this slope approached one. There was significant variability around the wetting front/removal time relationship, which was most likely due to a number of other factors that do play a role in controlling the removal process such as bulk density, pipe roughness, and moisture content at plug formation. Overall, the plugs likely removed due to lubrication along the pipe wall. The sand plugs require less of the plug to be saturated before the removal than the sandy loam plugs.

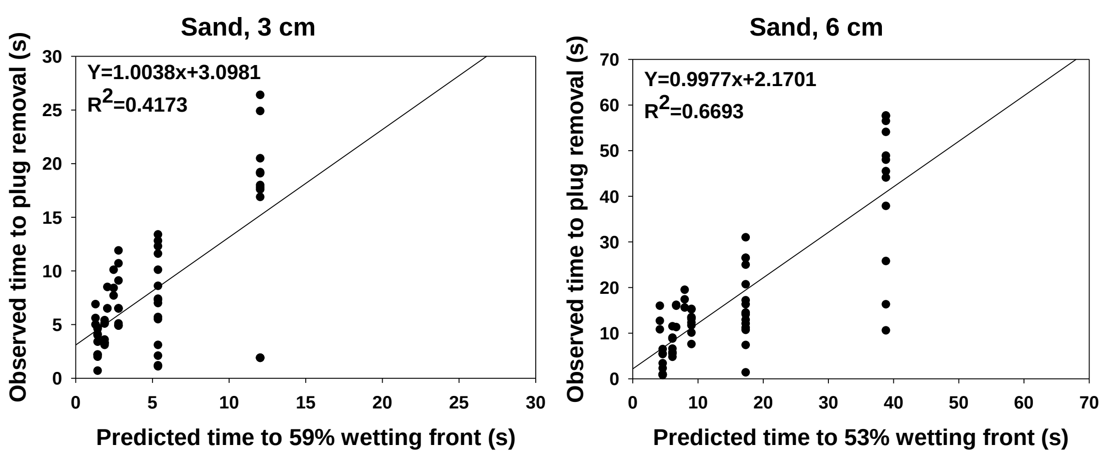

Figure 43. Sand 3 cm (left) and sand 6 cm (right): time predicted to achieve wetting front percentages compared to observed times to plug removal.

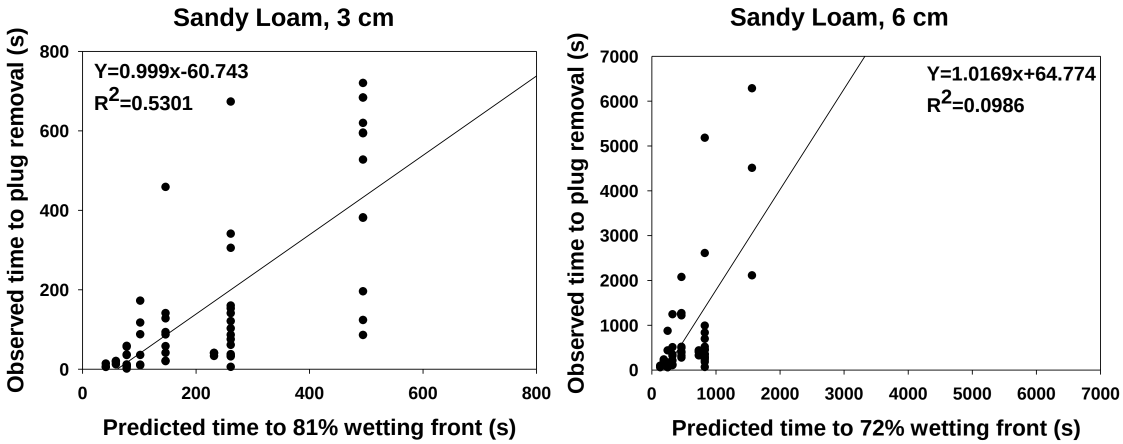

Figure 44. Sandy loam 3 cm (left) and sandy loam 6 cm (right): time predicted to achieve wetting front percentages compared to observed times to plug removal.

CHAPTER IV

CONCLUSIONS

Soil pipe plug characteristics, such as soil texture, bulk density, length, and moisture content, are important factors for predicting potential pore water pressure buildups in hillslopes. Sand plugs and non-cohesive plugs behaved consistently across the experimental variables. However, more cohesive sandy loam plugs were strongly influenced by plug length and bulk density. All plugs were removed intact after the wetting front reached certain distances within the plug; therefore, the hydraulics of water moving through the unsaturated plug will be an important factor to consider when creating a pipeflow model. Impulse may offer a way to model plug removal in future simulation models. There was a significant difference in impulse values between constant and dynamic head experiments for longer plug lengths and more cohesive soil types; therefore, the type of system acting on the plug, dynamic or constant head, will need to be accounted for in a pipeflow model. Some sandy loam plugs withstood pressures of 100 cm of H_2O for short durations, meaning that more cohesive plugs could require much higher pressures for removal. In constant head experiments, pressurized times reached upwards of 1000 s for some experiments; thus, water pressures have the potential to impact the surrounding soils for extended periods of time, potentially causing hillslope instability.

Future research needs include researching plug formation mechanisms, which will lead to characteristics of plugs associated with the clogging mechanism: bulk density of the plug, packing moisture content, plug length, and many others. Another important will be in analyzing the properties of the hillslope itself. Understanding the capabilities of the landscape to withstand pressures for certain lengths of time will be necessary to determine a factor of safety for that slope. A hillslope with the capability to withstand a head greater than the height of the hillslope would have a factor of safety greater than one.

This project is only a small part of the work that remains to be done before a full soil pipe model can be developed. With further advancements, a model will be able to determine if a landscape is experiencing pipe clogging and if it is susceptible to landscape failures. This will be an excellent risk management tool, and has the potential to save landscapes from failure by identifying areas of likely failure so that mitigation, such as adding a man-made drain, may occur. Such a model would prove invaluable in preventing the loss of lives, property, and natural resources due to a landscape failure due to pipe clogging.

REFERENCES

Aubertin G.M. (1971). Nature and extent of macropores in forest soils and their influence on subsurface water movement. US Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. Research Paper NE-192.

Beasley, R.S. (1976). Contribution of subsurface flow from the upper slopes of forested watersheds to channel flow. *Soil Science Society of America Journal*, 40:955-957.

Carter, M. and Bentley, S. (1991). Correlations of soil properties. Pentech Press. London, England.

Chamberlain, E. (1972), Soil survey—Organ Pipe Cactus National Monument, Pima County, Arizona—A special report. Soil Conservation Service, National Park Service, and Arizona Agricultural Experiment Station, M7-L-22776.

De Vries, J., and Chow, T.L. (1978). Hydrologic behavior of a forested mountain soil in coastal British Columbia. *Water Resources Research*. 14(5):935-942.

Detty, J.M., and McGuire, K.J. (2010). Topographic controls on shallow groundwater dynamics: implications of hydrologic connectivity between hillslopes and riparian zones in a till mantled catchment. *Hydrological Processes*. 24:2222-2236.

Foster, M., Fell, R., and Spannagle, M. (2000). The statistics of embankment dam failures and accidents. *Canadian Geotechnical Journal*, 37(5):1000–1024.

Fox, G.A., and Wilson, G.V. (2010). The role of subsurface flow in hillslope and stream bank erosion: A review. *Soil Science Society of America Journal*, 74(3):717-733.

Fredlund, D.G., and Rahardjo H. (1993). Soil Mechanics of Unsaturated Soils. JohnWiley & Sons: New York

Jones, J.A.A. (2010). Soil piping and catchment response. *Hydrological Processes*. 24(12):1548-1566.

Kosugi, K., Uchida, T., and Mizuyama, T. (2004). Numerical calculation of soil pipe flow and its effect on water dynamics in a slope. *Hydrological Processes*, 18(4):777–789. doi:10.1002/hyp.1367.

Matthews, G.P., Laudone, G.M., Gregory, A.S., Bird, N.R.A., Matthews, A.G.de G., and Whalley, W.R. (2010). Measurement and simulation of the effect of compaction on the pore structure and saturated hydraulic conductivity of grassland and arable soil. *Water Resources Research*. 46(5). doi:10.1029/2009WR00720.

Midgley, T.L., Fox, G.A., Wilson, G.V., Felice, R.M., and Heeren, D.M. (2013). In Situ Soil Pipeflow Experiments on Contrasting Streambank Soils. *Transactions of ASABE*, 56(2):479–488.

Pierson, T.C. (1983). Soil Pipes and Slope Stability. *Quarterly Journal of Engineering Geology and Hydrogeology*, 16:1–11.

Rawls, W.J., ASCE, M., Brakensiek, D.L., and Miller, N. (1983). Green-Ampt Infiltration Parameters from Soils Data. *Journal of Hydraulic Engineering*, 109(1):62-70.

Sharma, R.H., and Konietzky, H. (2011). Instrumented failure of hillslope models with soil-pipes. *Geomorphology*, 130(3-4):272–279. doi:10.1016/j.geomorph.2011.04.007.

Sharma, R.H., Konietzky, H., and Ken'ichirou, K. (2010). Numerical analysis of soil pipe effects on hillslope water dynamics. *Acta Geotechnica*, 5:33–42. doi:10.1007/s11440-009-0104-5.

Sun, H., Wong, L.N.Y., Shang, Y., Yu, B., and Wang, Z. (2012). Experimental studies of groundwater pipe flow network characteristics in gravelly soil slopes. *Landslides*, 9:475–483. doi:10.1007/s10346-011-0312-6.

Uchida,T., Kosugi, K., and Mizuyama, T. (1999). Runoff characteristics of pipeflow and effects of pipeflow on rainfall-runoff phenomena in a mountainous watershed. *Journal of Hydrology*. 222:18–36.

Uchida, T., Kosugi, K., and Mizuyama, T. (2001). Effects of pipeflow on hydrological process and its relation to landslide: a review of pipeflow studies in forested headwater catchments. *Hydrological Processes*, 15(11):2151–2174. doi:10.1002/hyp.281.

van Genuchtem, M.Th. (1980). A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. *Soil Sciences Society of America Journal*. 44:892-898.

Verachtert, E., Van Den Eeckhaut, M., Poesen, J., and Deckers, J. (2010). Factors controlling the spatial distribution of soil piping erosion on loess-derived soils: A case study from central Belgium. *Geomorphology*, 118:339–348. doi:10.1016/j.geomorph.2010.02.001.

Verachtert, E., Van Den Eeckhaut, M., Poesen, J., and Deckers, J. (2013). Spatial interaction between collapsed pipes and landslides in hilly regions with loess-derived soils. *Earth Surface Processes and Landforms*, 38(8):826–835. doi:10.1002/esp.3325.

Weiler, M., and McDonnell, J.J. (2007). Conceptualizing lateral preferential flow and flow networks and simulating the effects on gauged and ungauged hillslopes. *Water Resources Research*. 43: W03403. doi: 10.1029/ 2006WR004867.

Whipkey, R.Z. (1965). Subsurface stormflow from forested slopes. *International Association of Scientific Hydrology*. Bulletin, 10(2):74-85, doi: 10.1080/02626666509493392.

Whipkey, R.Z. (1969). Storm runoff from forested catchments by subsurface routes. In Floods and their Computation, *Studies and Reports in Hydrology*. Leningrad. UNESCO-IASH-WMO. 3:773-779.

Wilson, G.V. (2009). Mechanisms of ephemeral gully erosion caused by constant flow through a continuous soil-pipe. *Earth Surface Processes and Landforms*, 34:1858–1866. doi:10.1002/esp.

Wilson, G.V. and Fox, G.A.. 2013. Pore-water pressures associated with clogging of soil pipes. *Numerical analysis. Soil Science Society of America Journal*. 77(4): 1168-1181.

Wilson, G.V., Rigby, J.R., and Dabney, S.M. (2015a). Soil pipe collapses in a loess pasture of Goodwin Creek Watershed, Mississppi: Role of soil properties and past land use. *Earth Surface Processes and Landforms*. (In Press, Accepted on February 11, 2015).

Wilson, G.V., Rigby, J.R., Ursic, M., and Dabney, S.M. (2015b). Soil pipe flow tracer experiments: 1. Connectivity and transport characteristics. *Hydrological Processes*. (In Review).

Zhou, Y., Wilson, G.V., Fox, G.A., Rigby, J.R., and Dabney, S.M. (2016). Soil pipe flow tracer experiments: 2. Application of a streamflow transient storage zone model. *Hydrological Processes*. (In Press, Accepted on October 12, 2015).

APPENDICES

Appendix 1: Table of Experiments

Type	Head or Velocity	Roughness	Bulk Density	Moisture %	Soil Type	Plug Length (cm)	X-sect. Area (cm^2)
Constant	25	Sand	1.6	11.8	Sand	3	4.71
Constant	25	Sand	1.6	11.8	Sand	3	4.71
Constant	25	Sand	1.6	11.8	Sand	3	4.71
Constant	25	Sand	1.6	11.8	Sand	6	4.71
Constant	25	Sand	1.6	11.8	Sand	6	4.71
Constant	25	Sand	1.6	11.8	Sand	6	4.71
Constant	10	Sand	1.6	11.8	Sand	3	3.14
Constant	10	Sand	1.6	11.8	Sand	3	3.14
Constant	10	Sand	1.6	11.8	Sand	3	3.14
Constant	10	Sand	1.6	11.8	Sand	6	3.14
Constant	10	Sand	1.6	11.8	Sand	6	3.14
Constant	10	Sand	1.6	11.8	Sand	6	3.14
Constant	25	Sand	1.6	11.8	Sand	3	3.14
Constant	25	Sand	1.6	11.8	Sand	3	3.14
Constant	25	Sand	1.6	11.8	Sand	3	3.14
Constant	25	Sand	1.6	11.8	Sand	6	3.14
Constant	25	Sand	1.6	11.8	Sand	6	3.14
Constant	25	Sand	1.6	11.8	Sand	6	3.14
Constant	50	Sand	1.6	11.8	Sand	3	3.14
Constant	50	Sand	1.6	11.8	Sand	3	3.14
Constant	50	Sand	1.6	11.8	Sand	3	3.14
Constant	50	Sand	1.6	11.8	Sand	6	3.14
Constant	50	Sand	1.6	11.8	Sand	6	3.14
Constant	50	Sand	1.6	11.8	Sand	6	3.14
Constant	75	Sand	1.6	11.8	Sand	3	3.14
Constant	75	Sand	1.6	11.8	Sand	3	3.14
Constant	75	Sand	1.6	11.8	Sand	3	3.14
Constant	75	Sand	1.6	11.8	Sand	6	3.14
Constant	75	Sand	1.6	11.8	Sand	6	3.14
Constant	75	Sand	1.6	11.8	Sand	6	3.14
Constant	100	Sand	1.6	11.8	Sand	3	3.14
Constant	100	Sand	1.6	11.8	Sand	3	3.14
Constant	100	Sand	1.6	11.8	Sand	3	3.14
Constant	100	Sand	1.6	11.8	Sand	6	3.14
Constant	100	Sand	1.6	11.8	Sand	6	3.14
Constant	100	Sand	1.6	11.8	Sand	6	3.14
Dynamic	1	Sand	1.6	11.8	Sand	3	4.71
Dynamic	1	Sand	1.6	11.8	Sand	3	4.71
Dynamic	1	Sand	1.6	11.8	Sand	3	4.71
Dynamic	1	Sand	1.6	11.8	Sand	6	4.71
Dynamic	1	Sand	1.6	11.8	Sand	6	4.71
Dynamic	1	Sand	1.6	11.8	Sand	6	4.71
Dynamic	1	Sand	1.6	11.8	Sand	3	3.14
Dynamic	1	Sand	1.6	11.8	Sand	3	3.14

Dynamic	1	Sand	1.6	11.8	Sand	3	3.14
Dynamic	1	Sand	1.6	11.8	Sand	6	3.14
Dynamic	1	Sand	1.6	11.8	Sand	6	3.14
Dynamic	1	Sand	1.6	11.8	Sand	6	3.14
Constant	25	Sand	1.6	11.8	Sandy Loam	3	4.71
Constant	25	Sand	1.6	11.8	Sandy Loam	3	4.71
Constant	25	Sand	1.6	11.8	Sandy Loam	3	4.71
Constant	25	Sand	1.6	11.8	Sandy Loam	6	4.71
Constant	25	Sand	1.6	11.8	Sandy Loam	6	4.71
Constant	25	Sand	1.6	11.8	Sandy Loam	6	4.71
Constant	10	Sand	1.6	11.8	Sandy Loam	3	3.14
Constant	10	Sand	1.6	11.8	Sandy Loam	3	3.14
Constant	10	Sand	1.6	11.8	Sandy Loam	3	3.14
Constant	25	Sand	1.6	11.8	Sandy Loam	3	3.14
Constant	25	Sand	1.6	11.8	Sandy Loam	3	3.14
Constant	25	Sand	1.6	11.8	Sandy Loam	3	3.14
Constant	25	Sand	1.6	11.8	Sandy Loam	6	3.14
Constant	25	Sand	1.6	11.8	Sandy Loam	6	3.14
Constant	25	Sand	1.6	11.8	Sandy Loam	6	3.14
Constant	50	Sand	1.6	11.8	Sandy Loam	3	3.14
Constant	50	Sand	1.6	11.8	Sandy Loam	3	3.14
Constant	50	Sand	1.6	11.8	Sandy Loam	3	3.14
Constant	50	Sand	1.6	11.8	Sandy Loam	6	3.14
Constant	50	Sand	1.6	11.8	Sandy Loam	6	3.14
Constant	50	Sand	1.6	11.8	Sandy Loam	6	3.14
Constant	51	Sand	1.6	11.8	Sandy Loam	6	3.14
Constant	75	Sand	1.6	11.8	Sandy Loam	3	3.14
Constant	75	Sand	1.6	11.8	Sandy Loam	3	3.14
Constant	75	Sand	1.6	11.8	Sandy Loam	3	3.14
Constant	75	Sand	1.6	11.8	Sandy Loam	6	3.14
Constant	75	Sand	1.6	11.8	Sandy Loam	6	3.14
Constant	75	Sand	1.6	11.8	Sandy Loam	6	3.14
Constant	75	Sand	1.6	11.8	Sandy Loam	6	3.14
Constant	100	Sand	1.6	11.8	Sandy Loam	3	3.14
Constant	100	Sand	1.6	11.8	Sandy Loam	3	3.14
Constant	100	Sand	1.6	11.8	Sandy Loam	3	3.14
Constant	100	Sand	1.6	11.8	Sandy Loam	6	3.14
Constant	100	Sand	1.6	11.8	Sandy Loam	6	3.14
Constant	100	Sand	1.6	11.8	Sandy Loam	6	3.14
Dynamic	1	Sand	1.6	11.8	Sandy Loam	3	4.71
Dynamic	1	Sand	1.6	11.8	Sandy Loam	3	4.71
Dynamic	1	Sand	1.6	11.8	Sandy Loam	3	4.71
Dynamic	1	Sand	1.6	11.8	Sandy Loam	6	4.71
Dynamic	1	Sand	1.6	11.8	Sandy Loam	6	4.71
Dynamic	1	Sand	1.6	11.8	Sandy Loam	6	4.71
Dynamic	1	Sand	1.6	11.8	Sandy Loam	3	3.14
Dynamic	1	Sand	1.6	11.8	Sandy Loam	3	3.14
Dynamic	1	Sand	1.6	11.8	Sandy Loam	3	3.14
Dynamic	1	Sand	1.6	11.8	Sandy Loam	6	3.14
Dynamic	1	Sand	1.6	11.8	Sandy Loam	6	3.14
Dynamic	1	Sand	1.6	11.8	Sandy Loam	6	3.14
Constant	10	Sandy Loam	1.6	11.8	Sand	3	3.14
Constant	10	Sandy Loam	1.6	11.8	Sand	3	3.14
Constant	10	Sandy Loam	1.6	11.8	Sand	3	3.14
Constant	10	Sandy Loam	1.6	11.8	Sand	6	3.14
Constant	10	Sandy Loam	1.6	11.8	Sand	6	3.14
Constant	10	Sandy Loam	1.6	11.8	Sand	6	3.14
Constant	25	Sandy Loam	1.6	11.8	Sand	3	4.71
Constant	25	Sandy Loam	1.6	11.8	Sand	3	4.71
Constant	25	Sandy Loam	1.6	11.8	Sand	3	4.71
Constant	25	Sandy Loam	1.6	11.8	Sand	6	4.71
Constant	25	Sandy Loam	1.6	11.8	Sand	6	4.71
Constant	25	Sandy Loam	1.6	11.8	Sand	6	4.71

Constant	10	Sandy Loam	1.6	11.8	Sand	3	3.14
Constant	10	Sandy Loam	1.6	11.8	Sand	3	3.14
Constant	10	Sandy Loam	1.6	11.8	Sand	3	3.14
Constant	10	Sandy Loam	1.6	11.8	Sand	6	3.14
Constant	10	Sandy Loam	1.6	11.8	Sand	6	3.14
Constant	10	Sandy Loam	1.6	11.8	Sand	6	3.14
Constant	50	Sandy Loam	1.6	11.8	Sand	3	3.14
Constant	50	Sandy Loam	1.6	11.8	Sand	3	3.14
Constant	50	Sandy Loam	1.6	11.8	Sand	3	3.14
Constant	50	Sandy Loam	1.6	11.8	Sand	6	3.14
Constant	50	Sandy Loam	1.6	11.8	Sand	6	3.14
Constant	50	Sandy Loam	1.6	11.8	Sand	6	3.14
Constant	100	Sandy Loam	1.6	11.8	Sand	3	3.14
Constant	100	Sandy Loam	1.6	11.8	Sand	3	3.14
Constant	100	Sandy Loam	1.6	11.8	Sand	3	3.14
Constant	100	Sandy Loam	1.6	11.8	Sand	6	3.14
Constant	100	Sandy Loam	1.6	11.8	Sand	6	3.14
Constant	100	Sandy Loam	1.6	11.8	Sand	6	3.14
Dynamic	1	Sandy Loam	1.6	11.8	Sand	3	4.71
Dynamic	1	Sandy Loam	1.6	11.8	Sand	3	4.71
Dynamic	1	Sandy Loam	1.6	11.8	Sand	3	4.71
Dynamic	1	Sandy Loam	1.6	11.8	Sand	6	4.71
Dynamic	1	Sandy Loam	1.6	11.8	Sand	6	4.71
Dynamic	1	Sandy Loam	1.6	11.8	Sand	6	4.71
Dynamic	1	Sandy Loam	1.6	11.8	Sand	3	3.14
Dynamic	1	Sandy Loam	1.6	11.8	Sand	3	3.14
Dynamic	1	Sandy Loam	1.6	11.8	Sand	3	3.14
Dynamic	1	Sandy Loam	1.6	11.8	Sand	6	3.14
Dynamic	1	Sandy Loam	1.6	11.8	Sand	6	3.14
Dynamic	1	Sandy Loam	1.6	11.8	Sand	6	3.14
Constant	10	Sandy Loam	1.6	11.8	Sandy Loam	3	3.14
Constant	10	Sandy Loam	1.6	11.8	Sandy Loam	3	3.14
Constant	10	Sandy Loam	1.6	11.8	Sandy Loam	3	3.14
Constant	25	Sandy Loam	1.6	11.8	Sandy Loam	3	4.71
Constant	25	Sandy Loam	1.6	11.8	Sandy Loam	3	4.71
Constant	25	Sandy Loam	1.6	11.8	Sandy Loam	3	4.71
Constant	25	Sandy Loam	1.6	11.8	Sandy Loam	6	4.71
Constant	25	Sandy Loam	1.6	11.8	Sandy Loam	6	4.71
Constant	25	Sandy Loam	1.6	11.8	Sandy Loam	6	4.71
Constant	10	Sandy Loam	1.6	11.8	Sandy Loam	3	3.14
Constant	10	Sandy Loam	1.6	11.8	Sandy Loam	3	3.14
Constant	10	Sandy Loam	1.6	11.8	Sandy Loam	3	3.14
Constant	50	Sandy Loam	1.6	11.8	Sandy Loam	3	3.14
Constant	50	Sandy Loam	1.6	11.8	Sandy Loam	3	3.14
Constant	50	Sandy Loam	1.6	11.8	Sandy Loam	3	3.14
Constant	50	Sandy Loam	1.6	11.8	Sandy Loam	6	3.14
Constant	50	Sandy Loam	1.6	11.8	Sandy Loam	6	3.14
Constant	50	Sandy Loam	1.6	11.8	Sandy Loam	6	3.14
Constant	100	Sandy Loam	1.6	11.8	Sandy Loam	3	3.14
Constant	100	Sandy Loam	1.6	11.8	Sandy Loam	3	3.14
Constant	100	Sandy Loam	1.6	11.8	Sandy Loam	3	3.14
Constant	100	Sandy Loam	1.6	11.8	Sandy Loam	3	3.14
Constant	100	Sandy Loam	1.6	11.8	Sandy Loam	6	3.14
Constant	100	Sandy Loam	1.6	11.8	Sandy Loam	6	3.14
Constant	100	Sandy Loam	1.6	11.8	Sandy Loam	6	3.14
Dynamic	1	Sandy Loam	1.6	11.8	Sandy Loam	3	4.71
Dynamic	1	Sandy Loam	1.6	11.8	Sandy Loam	3	4.71
Dynamic	1	Sandy Loam	1.6	11.8	Sandy Loam	3	4.71
Dynamic	1	Sandy Loam	1.6	11.8	Sandy Loam	6	4.71
Dynamic	1	Sandy Loam	1.6	11.8	Sandy Loam	6	4.71
Dynamic	1	Sandy Loam	1.6	11.8	Sandy Loam	6	4.71
Dynamic	1	Sandy Loam	1.6	11.8	Sandy Loam	3	3.14
Dynamic	1	Sandy Loam	1.6	11.8	Sandy Loam	3	3.14

Dynamic	1	Sandy Loam	1.6	11.8	Sandy Loam	3	3.14
Dynamic	1	Sandy Loam	1.6	11.8	Sandy Loam	6	3.14
Dynamic	1	Sandy Loam	1.6	11.8	Sandy Loam	6	3.14
Dynamic	1	Sandy Loam	1.6	11.8	Sandy Loam	6	3.14
Constant	100	smooth	1.6	11.8	Sand	3	3.14
Constant	100	smooth	1.6	11.8	Sand	3	3.14
Constant	100	smooth	1.6	11.8	Sand	3	3.14
Constant	75	smooth	1.6	11.8	Sand	3	3.14
Constant	75	smooth	1.6	11.8	Sand	3	3.14
Constant	75	smooth	1.6	11.8	Sand	3	3.14
Constant	75	smooth	1.6	11.8	Sand	3	3.14
Constant	50	smooth	1.6	11.8	Sand	3	3.14
Constant	50	smooth	1.6	11.8	Sand	3	3.14
Constant	50	smooth	1.6	11.8	Sand	3	3.14
Constant	25	smooth	1.6	11.8	Sand	3	3.14
Constant	25	smooth	1.6	11.8	Sand	3	3.14
Constant	25	smooth	1.6	11.8	Sand	3	3.14
Constant	10	smooth	1.6	11.8	Sand	3	3.14
Constant	10	smooth	1.6	11.8	Sand	3	3.14
Constant	10	smooth	1.6	11.8	Sand	3	3.14
Constant	25	smooth	1.6	11.8	Sand	3	4.71
Constant	25	smooth	1.6	11.8	Sand	3	4.71
Constant	25	smooth	1.6	11.8	Sand	3	4.71
Constant	100	smooth	1.6	11.8	Sand	6	3.14
Constant	100	smooth	1.6	11.8	Sand	6	3.14
Constant	100	smooth	1.6	11.8	Sand	6	3.14
Constant	75	smooth	1.6	11.8	Sand	6	3.14
Constant	75	smooth	1.6	11.8	Sand	6	3.14
Constant	75	smooth	1.6	11.8	Sand	6	3.14
Constant	75	smooth	1.6	11.8	Sand	6	3.14
Constant	50	smooth	1.6	11.8	Sand	6	3.14
Constant	50	smooth	1.6	11.8	Sand	6	3.14
Constant	50	smooth	1.6	11.8	Sand	6	3.14
Constant	25	smooth	1.6	11.8	Sand	6	3.14
Constant	25	smooth	1.6	11.8	Sand	6	3.14
Constant	25	smooth	1.6	11.8	Sand	6	3.14
Constant	10	smooth	1.6	11.8	Sand	6	3.14
Constant	10	smooth	1.6	11.8	Sand	6	3.14
Constant	10	smooth	1.6	11.8	Sand	6	3.14
Constant	25	smooth	1.6	11.8	Sand	6	4.71
Constant	25	smooth	1.6	11.8	Sand	6	4.71
Constant	25	smooth	1.6	11.8	Sand	6	4.71
Constant	25	smooth	1.3	11.8	Sand	3	3.14
Constant	25	smooth	1.3	11.8	Sand	3	3.14
Constant	25	smooth	1.3	11.8	Sand	3	3.14
Constant	25	smooth	1.3	11.8	Sand	6	3.14
Constant	25	smooth	1.3	11.8	Sand	6	3.14
Constant	25	smooth	1.3	11.8	Sand	6	3.14
Constant	25	smooth	1.4	11.8	Sand	3	3.14
Constant	25	smooth	1.4	11.8	Sand	3	3.14
Constant	25	smooth	1.4	11.8	Sand	3	3.14
Constant	25	smooth	1.4	11.8	Sand	6	3.14
Constant	25	smooth	1.4	11.8	Sand	6	3.14
Constant	25	smooth	1.4	11.8	Sand	6	3.14
Constant	25	smooth	1.5	11.8	Sand	3	3.14
Constant	25	smooth	1.5	11.8	Sand	3	3.14
Constant	25	smooth	1.5	11.8	Sand	3	3.14
Constant	25	smooth	1.5	11.8	Sand	6	3.14
Constant	25	smooth	1.5	11.8	Sand	6	3.14
Constant	25	smooth	1.5	11.8	Sand	6	3.14
Dynamic	1	smooth	1.6	11.8	Sand	3	3.14
Dynamic	1	smooth	1.6	11.8	Sand	3	3.14
Dynamic	1	smooth	1.6	11.8	Sand	3	3.14

Dynamic	0.75	smooth	1.6	11.8	Sand	3	3.14
Dynamic	0.75	smooth	1.6	11.8	Sand	3	3.14
Dynamic	0.75	smooth	1.6	11.8	Sand	3	3.14
Dynamic	1.5	smooth	1.6	11.8	Sand	3	3.14
Dynamic	1.5	smooth	1.6	11.8	Sand	3	3.14
Dynamic	1.5	smooth	1.6	11.8	Sand	3	3.14
Dynamic	1	smooth	1.6	11.8	Sand	3	4.71
Dynamic	1	smooth	1.6	11.8	Sand	3	4.71
Dynamic	1	smooth	1.6	11.8	Sand	3	4.71
Dynamic	1	smooth	1.6	11.8	Sand	6	3.14
Dynamic	1	smooth	1.6	11.8	Sand	6	3.14
Dynamic	1	smooth	1.6	11.8	Sand	6	3.14
Dynamic	0.75	smooth	1.6	11.8	Sand	6	3.14
Dynamic	0.75	smooth	1.6	11.8	Sand	6	3.14
Dynamic	0.75	smooth	1.6	11.8	Sand	6	3.14
Dynamic	1.5	smooth	1.6	11.8	Sand	6	3.14
Dynamic	1.5	smooth	1.6	11.8	Sand	6	3.14
Dynamic	1.5	smooth	1.6	11.8	Sand	6	3.14
Dynamic	1	smooth	1.6	11.8	Sand	6	4.71
Dynamic	1	smooth	1.6	11.8	Sand	6	4.71
Dynamic	1	smooth	1.6	11.8	Sand	6	4.71
Dynamic	1	smooth	1.4	11.8	Sand	3	3.14
Dynamic	1	smooth	1.4	11.8	Sand	3	3.14
Dynamic	1	smooth	1.4	11.8	Sand	3	3.14
Dynamic	1	smooth	1.4	11.8	Sand	6	3.14
Dynamic	1	smooth	1.4	11.8	Sand	6	3.14
Dynamic	1	smooth	1.4	11.8	Sand	6	3.14
Dynamic	1	smooth	1.5	11.8	Sand	3	3.14
Dynamic	1	smooth	1.5	11.8	Sand	3	3.14
Dynamic	1	smooth	1.5	11.8	Sand	3	3.14
Dynamic	1	smooth	1.5	11.8	Sand	6	3.14
Dynamic	1	smooth	1.5	11.8	Sand	6	3.14
Dynamic	1	smooth	1.5	11.8	Sand	6	3.14
Dynamic	1	smooth	1.6	15	Sand	3	3.14
Dynamic	1	smooth	1.6	15	Sand	3	3.14
Dynamic	1	smooth	1.6	15	Sand	3	3.14
Dynamic	1	smooth	1.6	15	Sand	6	3.14
Dynamic	1	smooth	1.6	15	Sand	6	3.14
Dynamic	1	smooth	1.6	15	Sand	6	3.14
Dynamic	1	smooth	1.6	20	Sand	3	3.14
Dynamic	1	smooth	1.6	20	Sand	3	3.14
Dynamic	1	smooth	1.6	20	Sand	3	3.14
Dynamic	1	smooth	1.6	20	Sand	6	3.14
Dynamic	1	smooth	1.6	20	Sand	6	3.14
Dynamic	1	smooth	1.6	20	Sand	6	3.14
Dynamic	1	smooth	1.3	11.8	Sand	3	3.14
Dynamic	1	smooth	1.3	11.8	Sand	3	3.14
Dynamic	1	smooth	1.3	11.8	Sand	3	3.14
Dynamic	1	smooth	1.3	11.8	Sand	6	3.14
Dynamic	1	smooth	1.3	11.8	Sand	6	3.14
Dynamic	1	smooth	1.3	11.8	Sand	6	3.14
Constant	100	smooth	1.6	11.8	Sandy Loam	3	3.14
Constant	100	smooth	1.6	11.8	Sandy Loam	3	3.14
Constant	100	smooth	1.6	11.8	Sandy Loam	3	3.14
Constant	75	smooth	1.6	11.8	Sandy Loam	3	3.14
Constant	75	smooth	1.6	11.8	Sandy Loam	3	3.14
Constant	75	smooth	1.6	11.8	Sandy Loam	3	3.14
Constant	50	smooth	1.6	11.8	Sandy Loam	3	3.14
Constant	50	smooth	1.6	11.8	Sandy Loam	3	3.14
Constant	50	smooth	1.6	11.8	Sandy Loam	3	3.14
Constant	25	smooth	1.6	11.8	Sandy Loam	3	3.14
Constant	25	smooth	1.6	11.8	Sandy Loam	3	3.14

Constant	25	smooth	1.6	11.8	Sandy Loam	3	3.14
Constant	10	smooth	1.6	11.8	Sandy Loam	3	3.14
Constant	10	smooth	1.6	11.8	Sandy Loam	3	3.14
Constant	10	smooth	1.6	11.8	Sandy Loam	3	3.14
Constant	25	smooth	1.6	11.8	Sandy Loam	3	4.71
Constant	25	smooth	1.6	11.8	Sandy Loam	3	4.71
Constant	25	smooth	1.6	11.8	Sandy Loam	3	4.71
Constant	100	smooth	1.6	11.8	Sandy Loam	6	3.14
Constant	100	smooth	1.6	11.8	Sandy Loam	6	3.14
Constant	100	smooth	1.6	11.8	Sandy Loam	6	3.14
Constant	75	smooth	1.6	11.8	Sandy Loam	6	3.14
Constant	75	smooth	1.6	11.8	Sandy Loam	6	3.14
Constant	75	smooth	1.6	11.8	Sandy Loam	6	3.14
Constant	75	smooth	1.6	11.8	Sandy Loam	6	3.14
Constant	50	smooth	1.6	11.8	Sandy Loam	6	3.14
Constant	50	smooth	1.6	11.8	Sandy Loam	6	3.14
Constant	50	smooth	1.6	11.8	Sandy Loam	6	3.14
Constant	25	smooth	1.6	11.8	Sandy Loam	6	3.14
Constant	25	smooth	1.6	11.8	Sandy Loam	6	3.14
Constant	25	smooth	1.6	11.8	Sandy Loam	6	3.14
Constant	10	smooth	1.6	11.8	Sandy Loam	6	3.14
Constant	10	smooth	1.6	11.8	Sandy Loam	6	3.14
Constant	10	smooth	1.6	11.8	Sandy Loam	6	3.14
Constant	25	smooth	1.6	11.8	Sandy Loam	6	4.71
Constant	25	smooth	1.6	11.8	Sandy Loam	6	4.71
Constant	25	smooth	1.6	11.8	Sandy Loam	6	4.71
Constant	25	smooth	1.3	11.8	Sandy Loam	3	3.14
Constant	25	smooth	1.3	11.8	Sandy Loam	3	3.14
Constant	25	smooth	1.3	11.8	Sandy Loam	3	3.14
Constant	25	smooth	1.3	11.8	Sandy Loam	6	3.14
Constant	25	smooth	1.3	11.8	Sandy Loam	6	3.14
Constant	25	smooth	1.3	11.8	Sandy Loam	6	3.14
Constant	25	smooth	1.4	11.8	Sandy Loam	3	3.14
Constant	25	smooth	1.4	11.8	Sandy Loam	3	3.14
Constant	25	smooth	1.4	11.8	Sandy Loam	3	3.14
Constant	25	smooth	1.4	11.8	Sandy Loam	6	3.14
Constant	25	smooth	1.4	11.8	Sandy Loam	6	3.14
Constant	25	smooth	1.4	11.8	Sandy Loam	6	3.14
Constant	25	smooth	1.5	11.8	Sandy Loam	3	3.14
Constant	25	smooth	1.5	11.8	Sandy Loam	3	3.14
Constant	25	smooth	1.5	11.8	Sandy Loam	3	3.14
Constant	25	smooth	1.5	11.8	Sandy Loam	6	3.14
Constant	25	smooth	1.5	11.8	Sandy Loam	6	3.14
Constant	25	smooth	1.5	11.8	Sandy Loam	6	3.14
Dynamic	1	smooth	1.6	11.8	Sandy Loam	3	3.14
Dynamic	1	smooth	1.6	11.8	Sandy Loam	3	3.14
Dynamic	1	smooth	1.6	11.8	Sandy Loam	3	3.14
Dynamic	0.75	smooth	1.6	11.8	Sandy Loam	3	3.14
Dynamic	0.75	smooth	1.6	11.8	Sandy Loam	3	3.14
Dynamic	0.75	smooth	1.6	11.8	Sandy Loam	3	3.14
Dynamic	1.5	smooth	1.6	11.8	Sandy Loam	3	3.14
Dynamic	1.5	smooth	1.6	11.8	Sandy Loam	3	3.14
Dynamic	1.5	smooth	1.6	11.8	Sandy Loam	3	3.14
Dynamic	1	smooth	1.6	11.8	Sandy Loam	3	4.71
Dynamic	1	smooth	1.6	11.8	Sandy Loam	3	4.71
Dynamic	1	smooth	1.6	11.8	Sandy Loam	3	4.71
Dynamic	1	smooth	1.6	11.8	Sandy Loam	6	3.14
Dynamic	1	smooth	1.6	11.8	Sandy Loam	6	3.14
Dynamic	1	smooth	1.6	11.8	Sandy Loam	6	3.14
Dynamic	0.75	smooth	1.6	11.8	Sandy Loam	6	3.14
Dynamic	0.75	smooth	1.6	11.8	Sandy Loam	6	3.14
Dynamic	0.75	smooth	1.6	11.8	Sandy Loam	6	3.14

Dynamic	1.5	smooth	1.6	11.8	Sandy Loam	6	3.14
Dynamic	1.5	smooth	1.6	11.8	Sandy Loam	6	3.14
Dynamic	1.5	smooth	1.6	11.8	Sandy Loam	6	3.14
Dynamic	1	smooth	1.6	11.8	Sandy Loam	6	4.71
Dynamic	1	smooth	1.6	11.8	Sandy Loam	6	4.71
Dynamic	1	smooth	1.6	11.8	Sandy Loam	6	4.71
Dynamic	1	smooth	1.4	11.8	Sandy Loam	3	3.14
Dynamic	1	smooth	1.4	11.8	Sandy Loam	3	3.14
Dynamic	1	smooth	1.4	11.8	Sandy Loam	3	3.14
Dynamic	1	smooth	1.4	11.8	Sandy Loam	6	3.14
Dynamic	1	smooth	1.4	11.8	Sandy Loam	6	3.14
Dynamic	1	smooth	1.4	11.8	Sandy Loam	6	3.14
Dynamic	1	smooth	1.5	11.8	Sandy Loam	3	3.14
Dynamic	1	smooth	1.5	11.8	Sandy Loam	3	3.14
Dynamic	1	smooth	1.5	11.8	Sandy Loam	3	3.14
Dynamic	1	smooth	1.5	11.8	Sandy Loam	6	3.14
Dynamic	1	smooth	1.5	11.8	Sandy Loam	6	3.14
Dynamic	1	smooth	1.5	11.8	Sandy Loam	6	3.14
Dynamic	1	smooth	1.6	15	Sandy Loam	3	3.14
Dynamic	1	smooth	1.6	15	Sandy Loam	3	3.14
Dynamic	1	smooth	1.6	15	Sandy Loam	3	3.14
Dynamic	1	smooth	1.6	15	Sandy Loam	6	3.14
Dynamic	1	smooth	1.6	15	Sandy Loam	6	3.14
Dynamic	1	smooth	1.6	15	Sandy Loam	6	3.14
Dynamic	1	smooth	1.6	20	Sandy Loam	3	3.14
Dynamic	1	smooth	1.6	20	Sandy Loam	3	3.14
Dynamic	1	smooth	1.6	20	Sandy Loam	3	3.14
Dynamic	1	smooth	1.6	20	Sandy Loam	6	3.14
Dynamic	1	smooth	1.6	20	Sandy Loam	6	3.14
Dynamic	1	smooth	1.6	20	Sandy Loam	6	3.14
Dynamic	1	smooth	1.3	11.8	Sandy Loam	3	3.14
Dynamic	1	smooth	1.3	11.8	Sandy Loam	3	3.14
Dynamic	1	smooth	1.3	11.8	Sandy Loam	3	3.14
Dynamic	1	smooth	1.3	11.8	Sandy Loam	6	3.14
Dynamic	1	smooth	1.3	11.8	Sandy Loam	6	3.14
Dynamic	1	smooth	1.3	11.8	Sandy Loam	6	3.14

VITA

Mikayla Marie Wanger

Candidate for the Degree of

Master of Science

Thesis: SOIL PIPING AND INTERNAL EROSION: LABORATORY EXPERIMENTS ON THE REMOVAL OF SOIL CLOGS

Major Field: Biosystems and Agricultural Engineering

Biographical:

Education:

Completed the requirements for the Master of Science in Biosystems Engineering at Oklahoma State University, Stillwater, Oklahoma in May, 2016.

Completed the requirements for the Bachelor of Science in Biosystems Engineering at Oklahoma State University, Stillwater, Oklahoma in May, 2013.

Experience:

2013-2016: National Science Foundation Graduate Research Fellow
2013: Undergraduate Research Scholar
2010-2012: Lew Wentz Undergraduate Research Scholar

Professional Memberships:

American Society of Agricultural and Biological Engineers
Biosystems and Agricultural Engineering Graduate Student Association